Rub & Buzz and Other Irregular Loudspeaker Distortion

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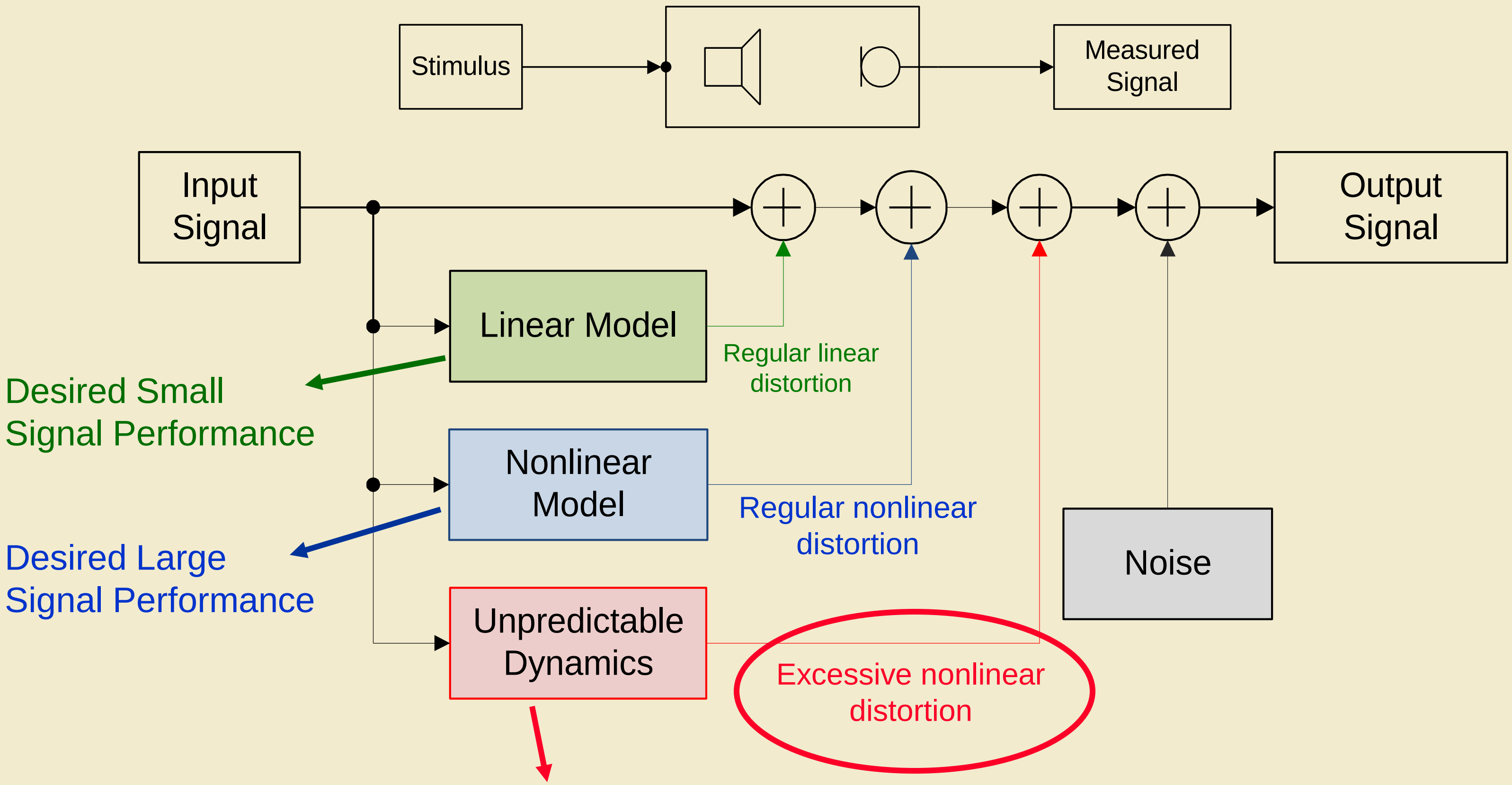
Problems addressed here:

- What is Rub & Buzz ?
- What kinds of symptoms are generated by irregular loudspeaker defects ?
- Why do straightforward measurements fail in detecting those defects ?
- Do we need a measurement more sensitive than the human ear ?
- How to cope with ambient production noise ?
- How to find the root cause and how to fix the problem ?

Desired and Undesired Components ?

Generation of Signal Distortion in an Audio System

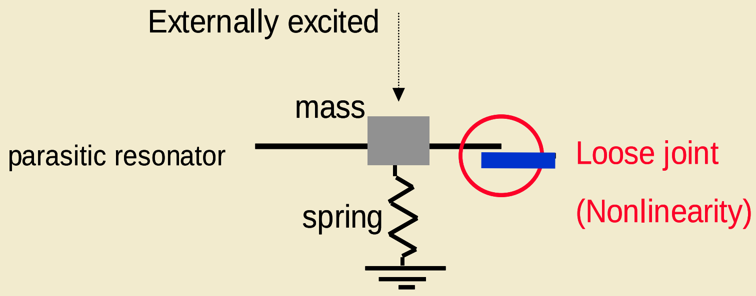


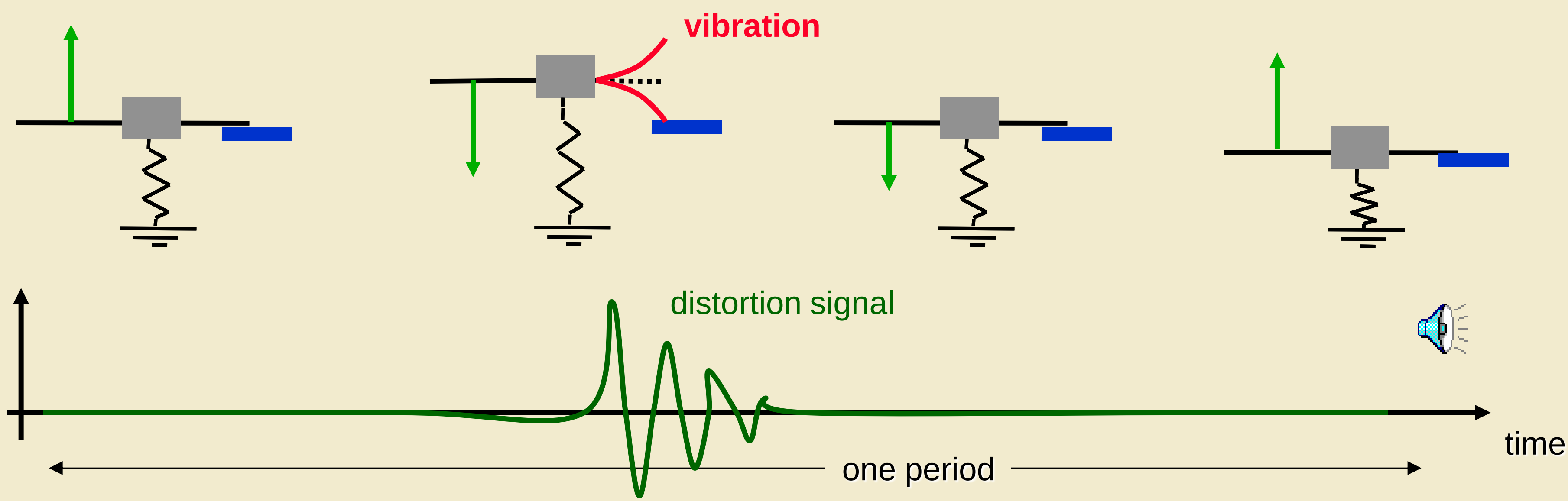
Undesired Loudspeaker Defects

- Rubbing coils , buzzing parts
- Wire beat, coil bottoming
- Loose particles, air leak noise
- Parasitic vibration of other components

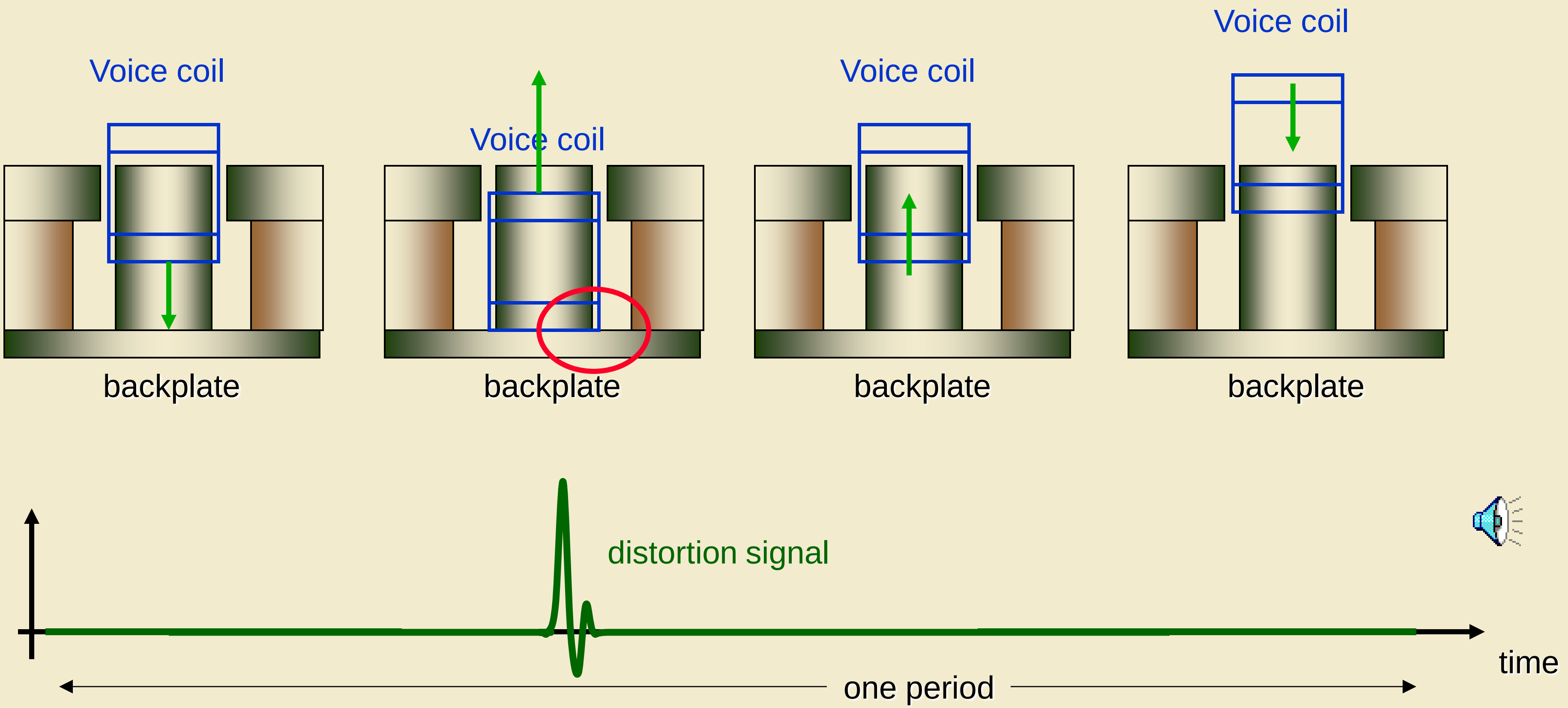
Loudspeaker Defect: *Buzz problem*

Most defects behave as a **nonlinear oscillator**
- active above a critical amplitude
- new mode of vibration
- powered and synchronized by stimulus
- constant output power





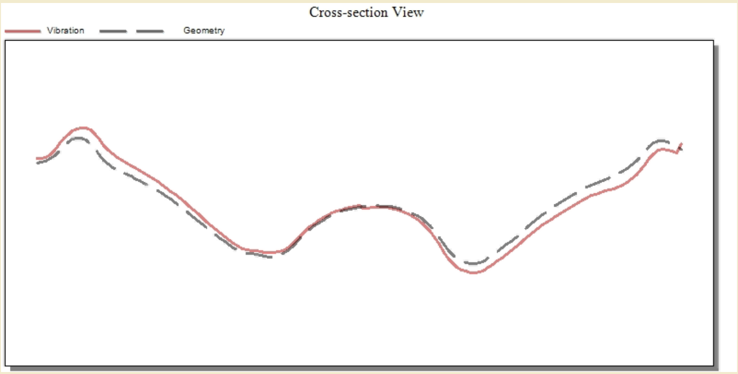
Loudspeaker Defect: Voice Coil Bottoming



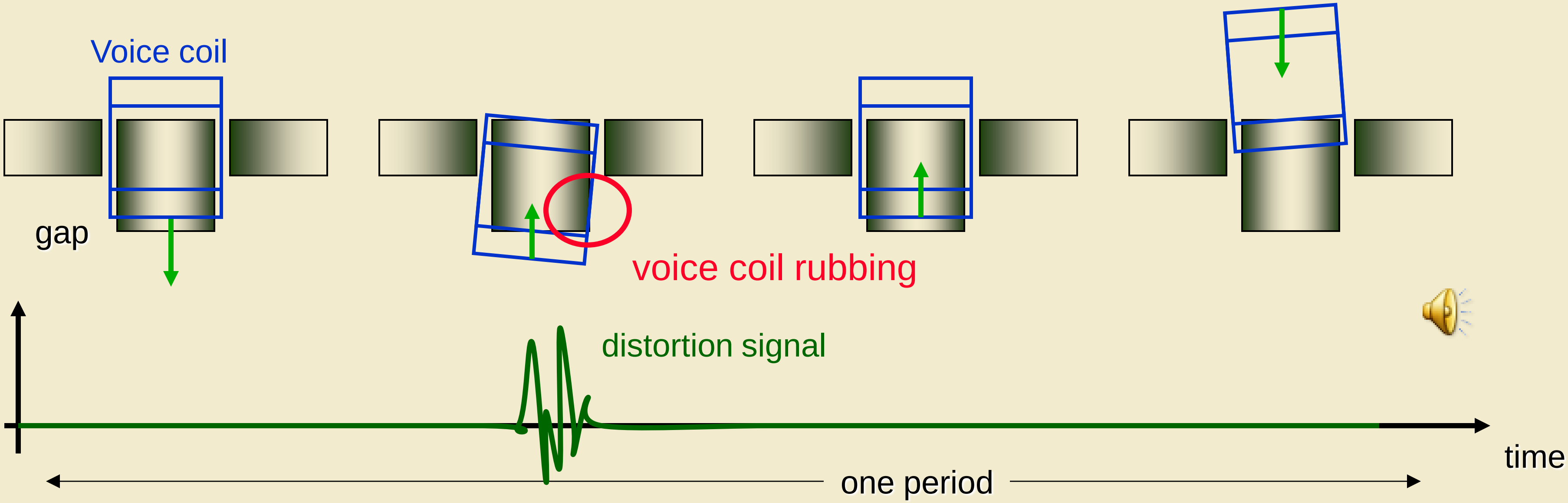
Short impulse, deterministic symptom

Loudspeaker Defect: Voice Coil Rubbing

Cause: rocking mode at 328 Hz

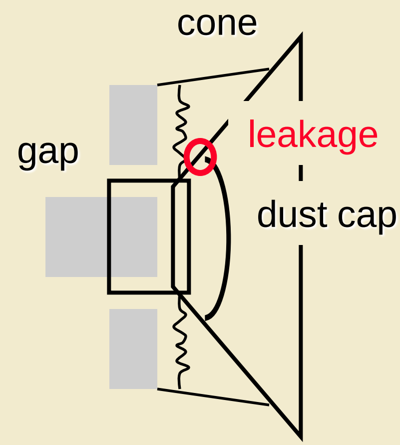


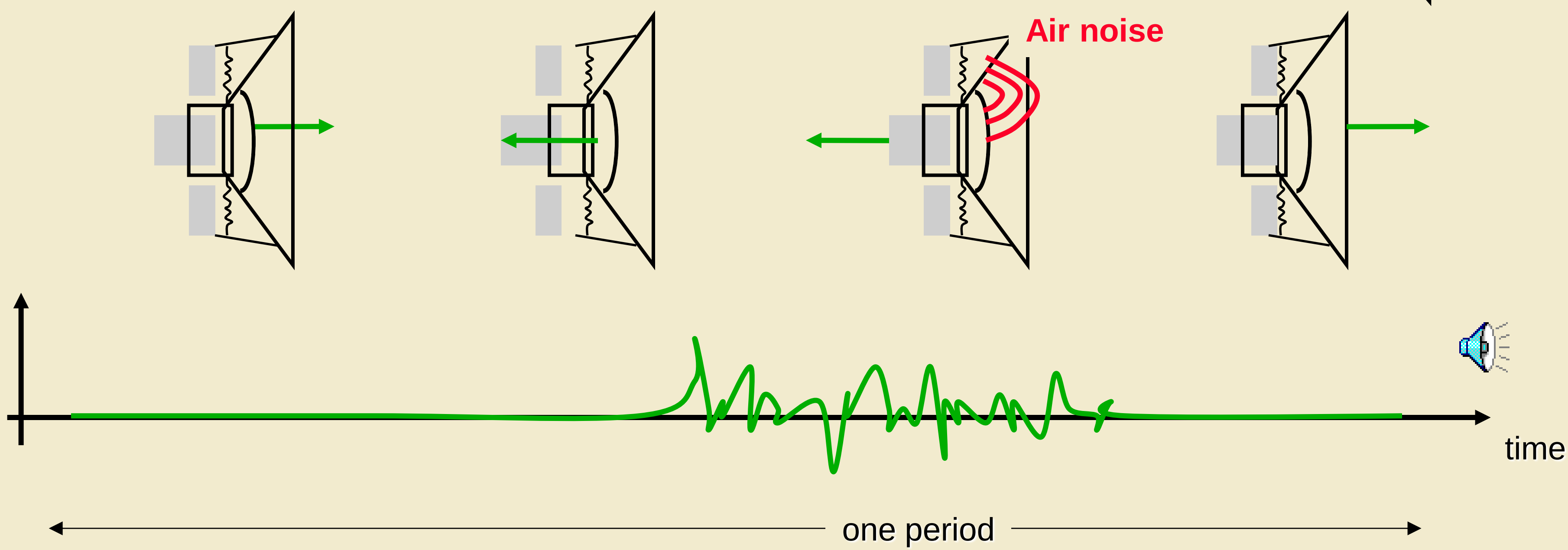
• signal contains reproducible and stochastic components



Loudspeaker Defect: Air Noise

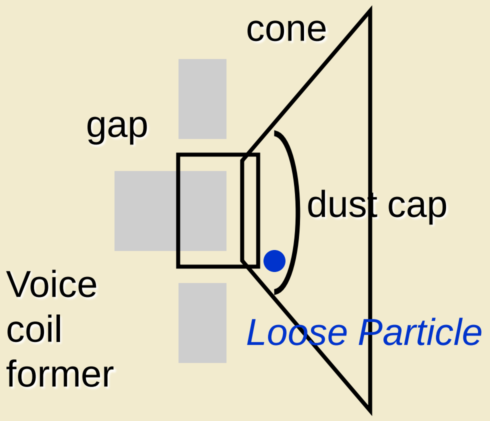
- stochastic signal
- air pressure is changed by coil displacement
- synchronized with stimulus – signal envelope

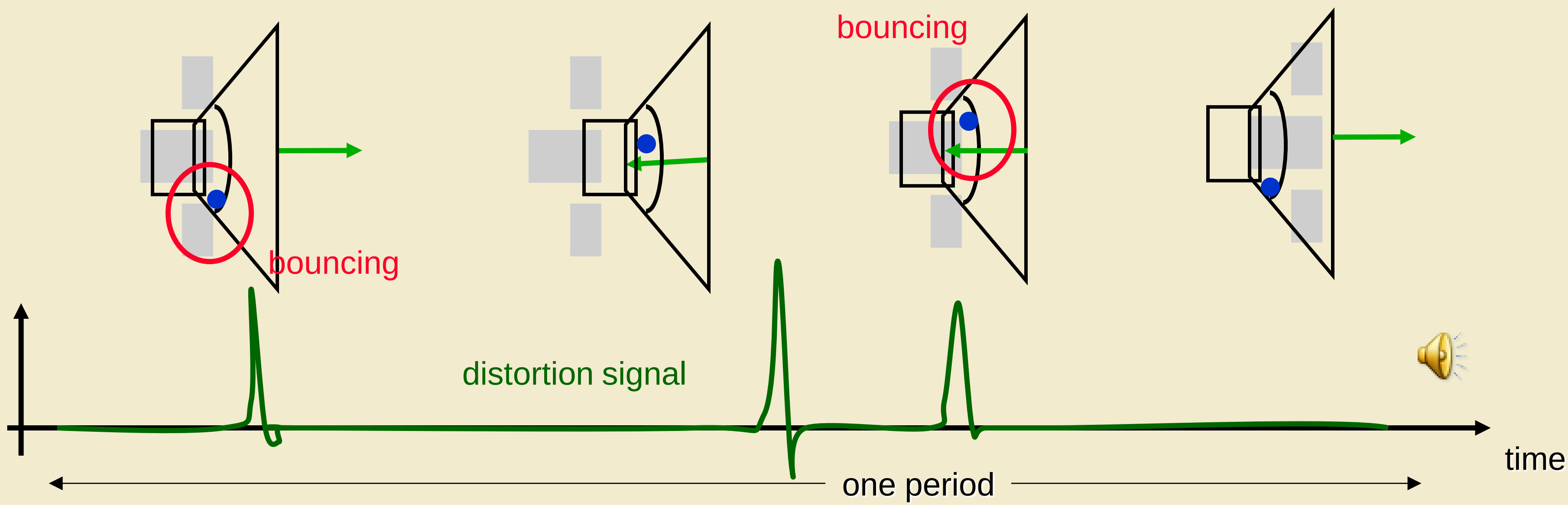




Loudspeaker Defect: Loose Particles

- random process
- impulsive
- particles are accelerated by cone displacement
- not synchronized with stimulus
- constant output power





Audibility and Impact on Sound Quality

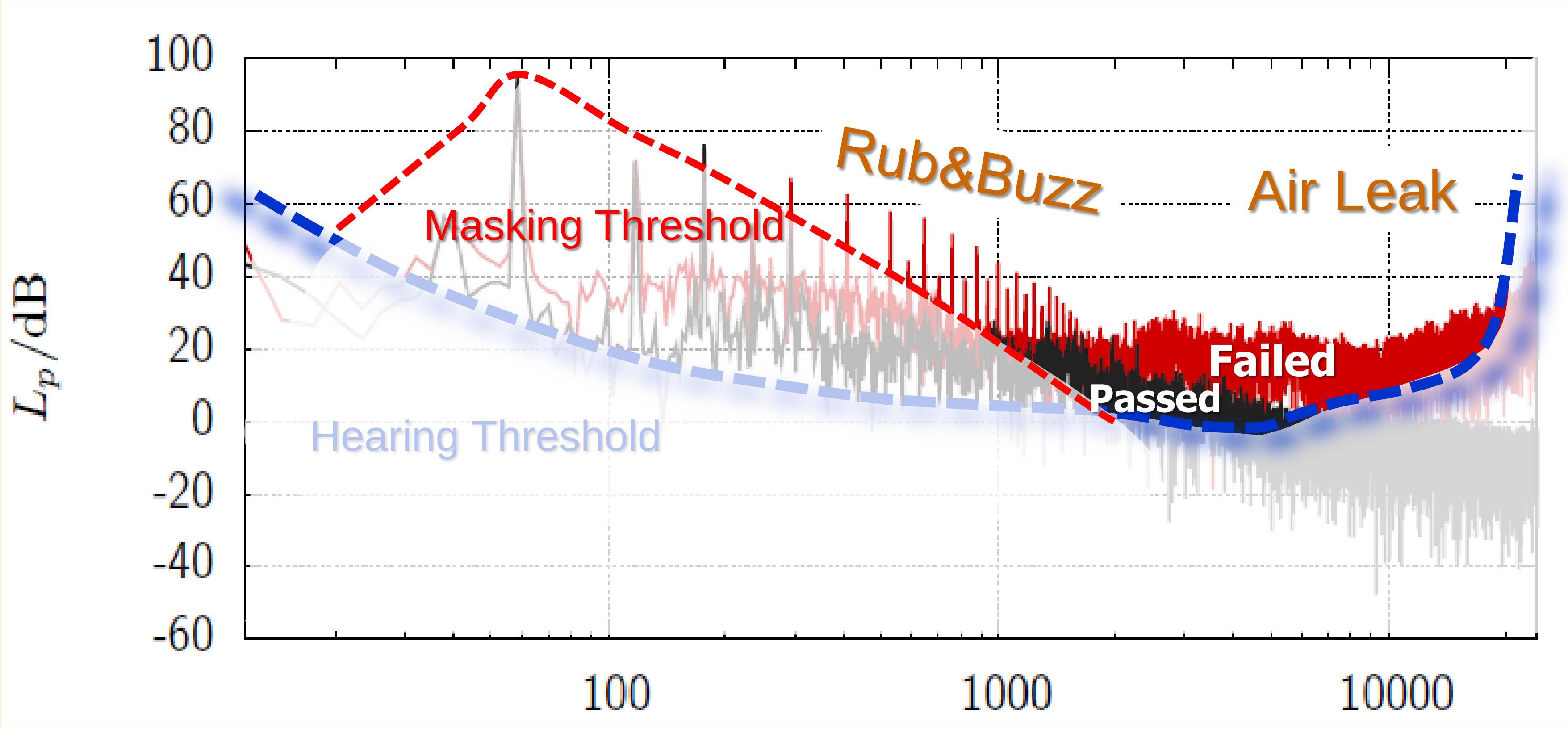
Searching for a Critical Stimulus

Audibility of Voice Coil Rubbing

Signal	Stimulus	Output 1V	Output 2V	Output 3V
Music				
Multi-Tone 20 Hz – 20 kHz				
Multi-Tone 20 Hz – 1 kHz				
Sinussoidal Sweep 1 s				

Most sensitive Stimulus

Masking of Loudspeaker Defects



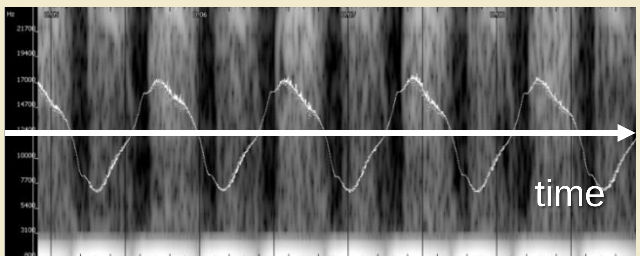
- irregular distortion produce high frequency components
- no masking from fundamental component at low frequencies
- close to the hearing threshold

Impact on Sound Quality

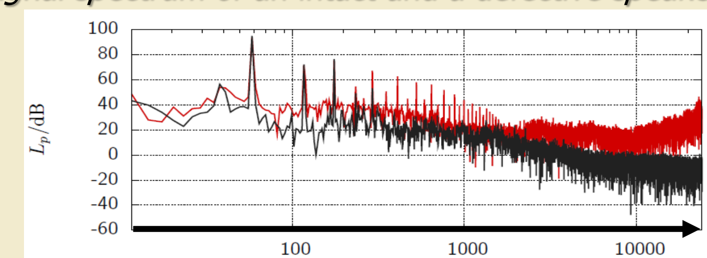
Amplitude modulation
(Envelope modulated by the bass signal 20…300 Hz)

High-Frequency components
(Increasing spectral power above 3 kHz)

Spectrogram and time signal of leak noise



Signal spectrum of an intact and a defective speaker



frequency

Increased Roughness

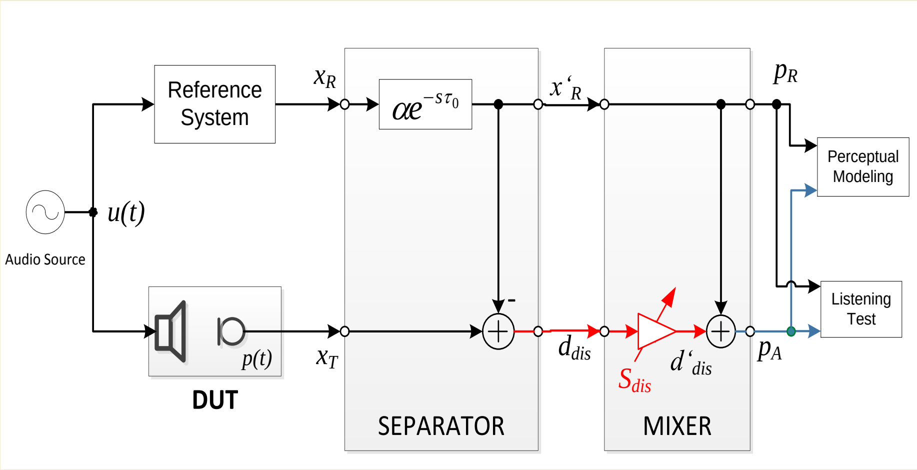
Increased Sharpness

Sensation: aggressive, unnatural, more noticeable

Degradation of Sound Quality

How to assess the impact on sound quality?

3rd Auralization Scheme



Steps:

1. Generating a reference signal (by measurement or modelling)
2. Synchronization and amplitude adjustment
3. Calculating the distoriton signal d_{dis} as the difference between test signal x_T and reference signal x'_R
4. Mixing the scaled distortion signal to the reference signal

PROs:

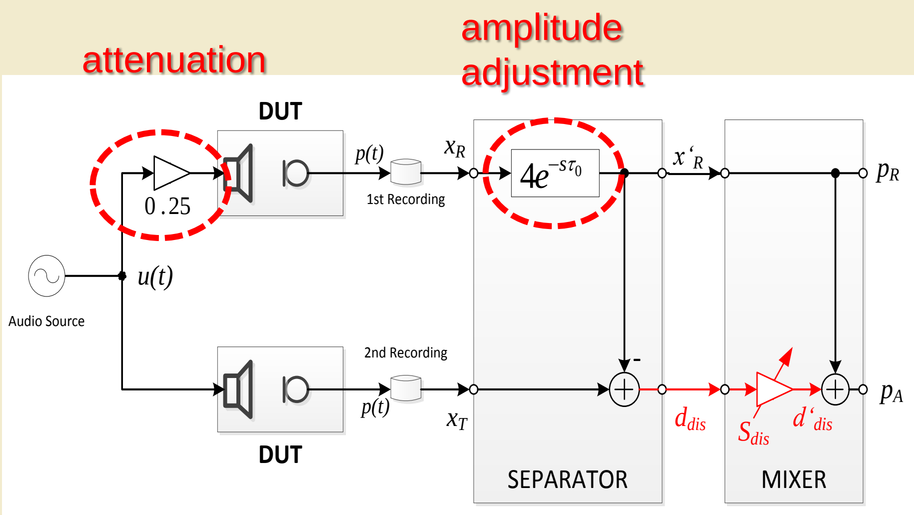
- no model required
- reference signal can be generated by measurement
- simple approach
- applicable to all kinds of distortion (including rub &buzz)

CONs:

- limited enhancement of linear distortion
- distortion may contain meausrement noise or modeling error

Regular and Irregular Nonlinear Distortion

3rd Auralization Scheme: Separation by Measured Reference Signal



- Reference signal is the recorded output of the DUT operated in the small signal domain
- Test signal is the recorded output of the DUT operated in the large signal domain

PROs:

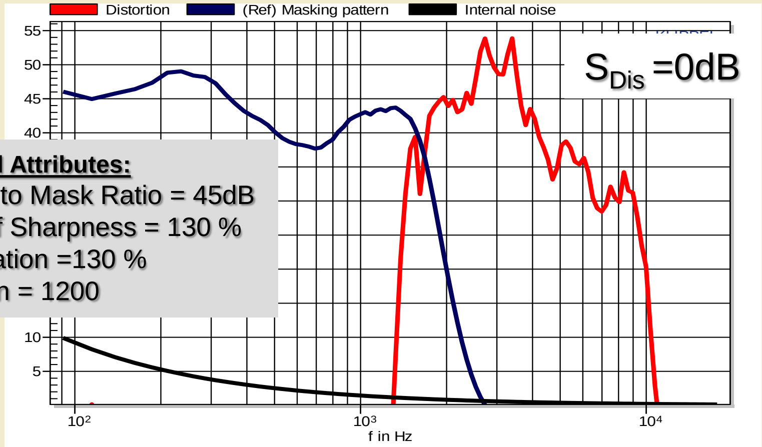
- no modeling required
- distortion is free of measurement noise
- considers irregular nonlinear distortion
- applicable to electronics, transducer, complete audio systems

CONs:

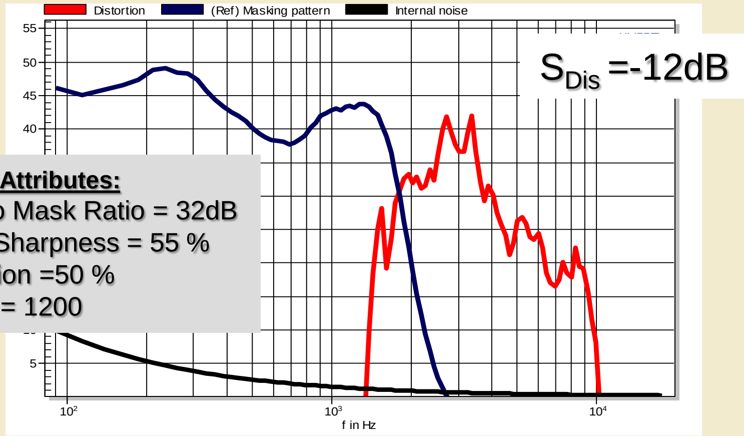
- Enhancement of measurement noise in distortion
- Recording required
- Measurement of DUT at the same position
- Thermal effects generate linear distortion
- Regular nonlinear distortion may mask irregular distortion

Auralization of Irregular Distortion (Rub & buzz)

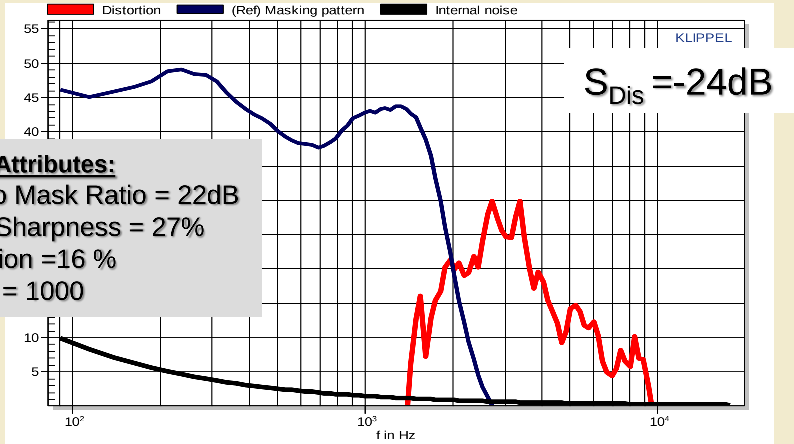
Example 1 : Headphone, sinusoidal sweep as stimulus



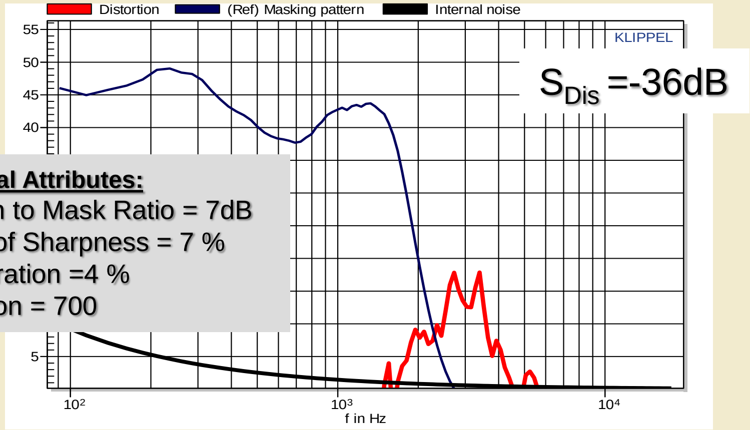
Perceptual Attributes:
Distortion to Mask Ratio = 45dB
Change of Sharpness = 130 %
Discolouration =130 %
Modulation = 1200



Perceptiual Attributes:
Distortion to Mask Ratio = 32dB
Change of Sharpness = 55 %
Discolouration =50 %
Modulation = 1200



Perceptual Attributes:
Distortion to Mask Ratio = 22dB
Change of Sharpness = 27%
Discolouration =16 %
Modulation = 1000

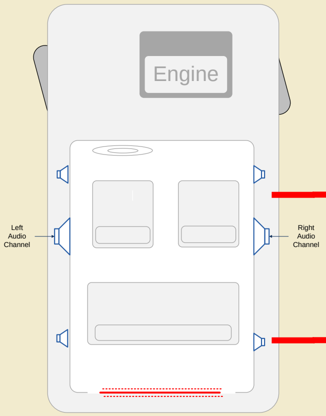


Perceptual Attributes:
Distortion to Mask Ratio = 7dB
Change of Sharpness = 7 %
Discolouration =4 %
Modulation = 700

Example 2: Automotive Audio System

organ music in woofer channel, Irregular distortion

End-of-line testing



Door Buzzing

- Test with sweep for loudspeaker defects and parasitic vibration → Measurement results
- Recording of reproduced music stimulus if defect is detected → recorded wave-file

Off-line Processing

Measurement results

recorded wave-file

↓

Auralization + Perceptive Evaluation

reference

S_{DIS} = 24 dB

S_{DIS} = 12 dB

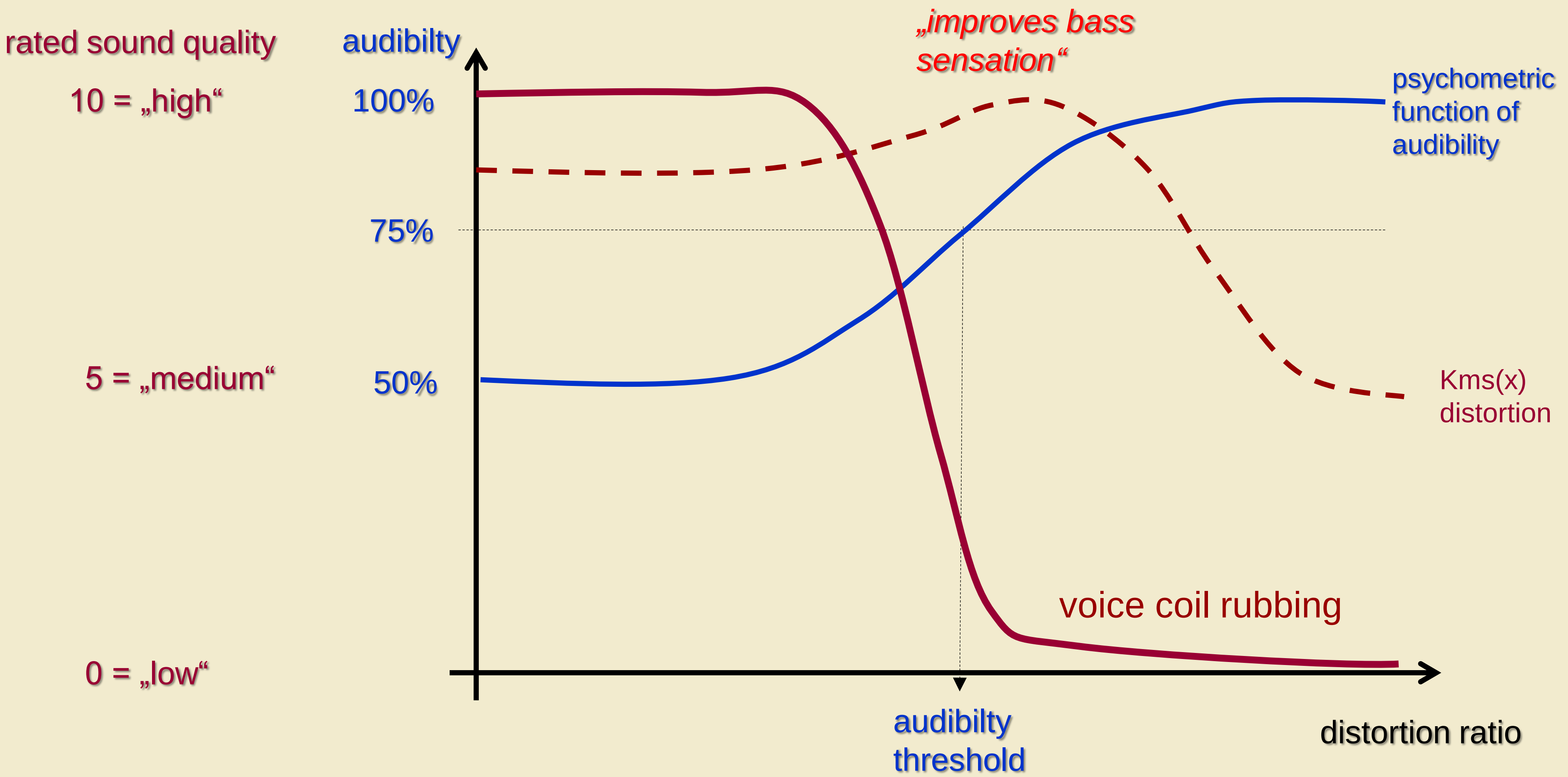
S_{DIS} = 0 dB

S_{DIS} = -6 dB

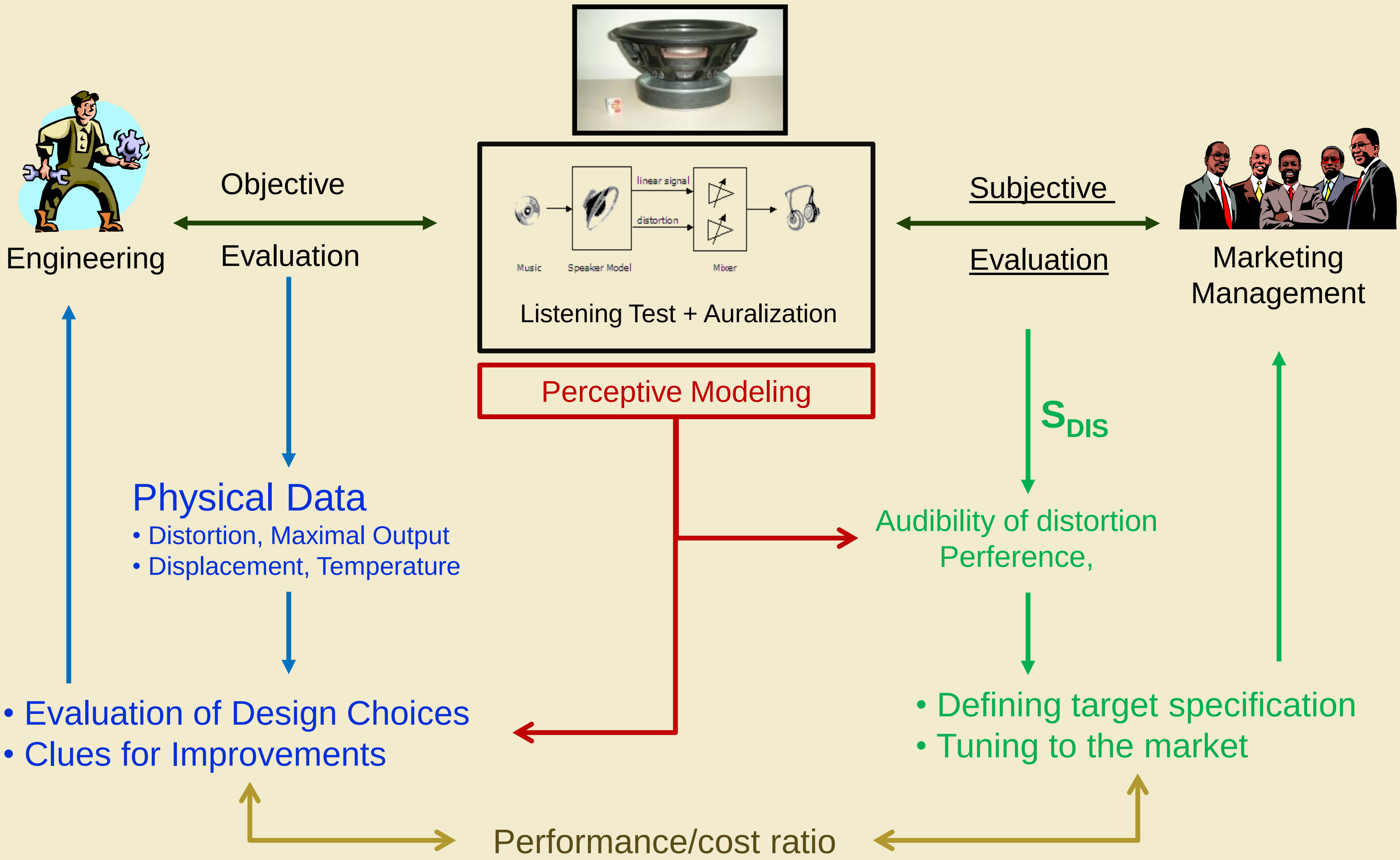
S_{DIS} = -12 dB

Sensations of Irregular Nonlinearities

while increasing the distortion signal



Subjective and Objective Evaluation
in Loudspeaker Development



Are loudspeaker defects are acceptable which are inaudible for a human ear in a production environment ?

NO !

- some loudspeaker defects become worse over time (after break-in of the suspension)
- some loudspeaker defects generate random symptoms (loose particles)
- the production noise masks the symptoms of the defect (air leakage)
- the end user may use a more critical stimulus (low frequency bass)
- Significant loss of sound quality if symptoms detected by customer

Consequences of Subjective Testing at the Assembling Line

- Need for trained operators more sensitive than the end user
- Avoiding fatigue of the human ears (regular breaks, low SPL)
- Operating the loudspeaker under similar condition as in the final application (listening distance, amplitude, load)
- Sufficient time for human inspection (flexible and long cycle times)

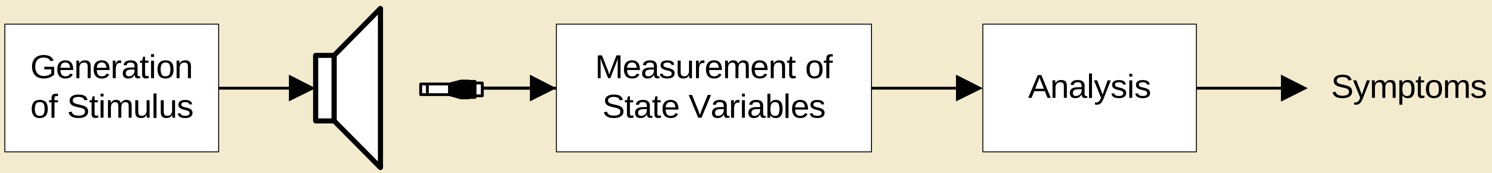
Human testing is expensive, not reliable and highly subjective !

Need for Objective Measurements

which

- are faster
- can be integrated in an automated line
- give reproducible, reliable results
- are more sensitive than the human ear
- are comparable with R&D, target performance
- are immune against ambient noise
- show the root cause of the defect
- are the basis for process control

Basic Requirements to detect Irregular Loudspeaker Defects

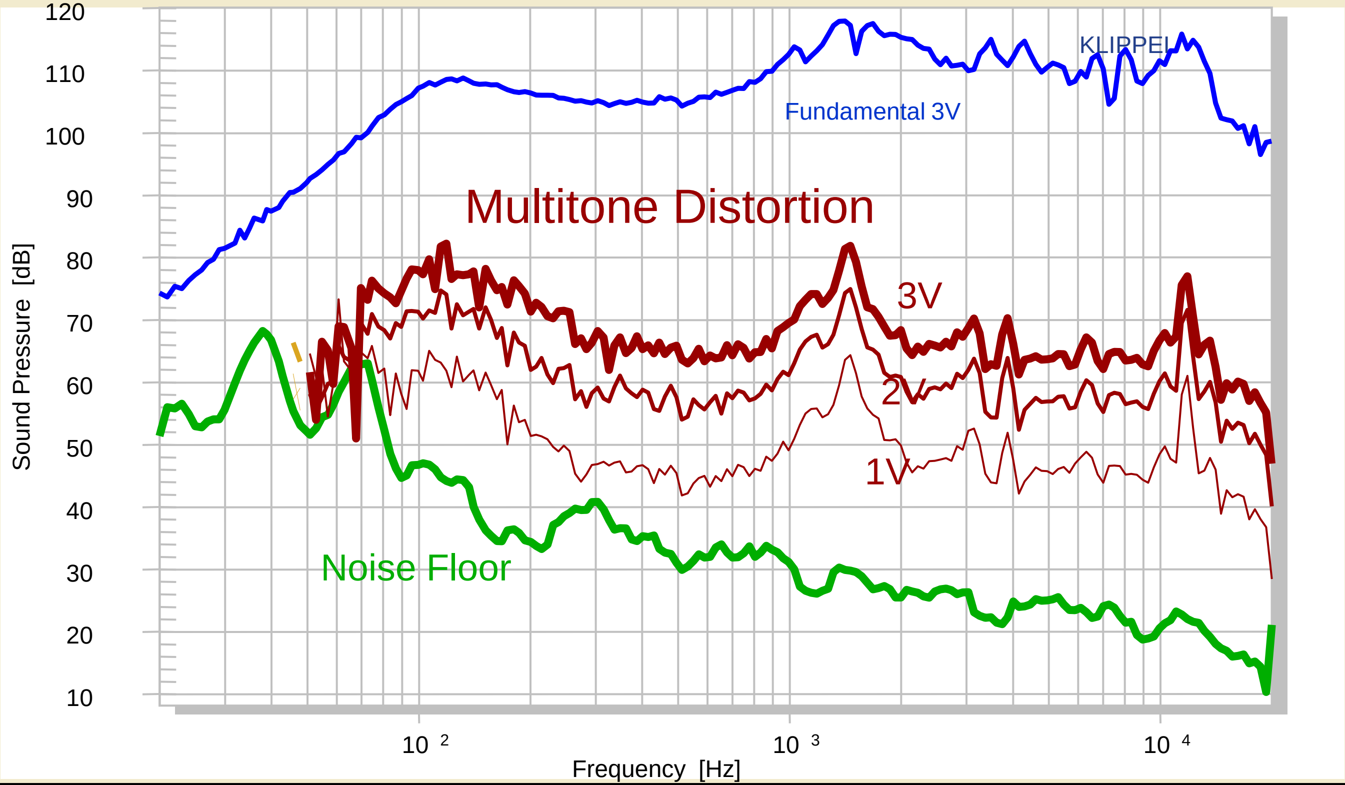


- High displacement x and/or velocity v is required
→ Stimulus with sufficient low frequency content
- Defects produce only acoustical symptoms
→ Sensitive microphone required
- Defects produce high frequency components
→ Low-pass filtered stimulus and high-pass filtered microphone signal
- Defects are similar to ambient noise
→ Microphone is located close to the source (near-field measurement)

Voice Coil Rubbing

multi-tone complex 20 Hz – 20 kHz

Stimulus:

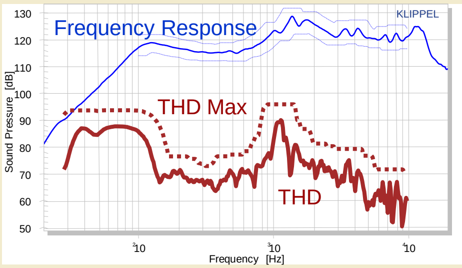


Regular distortion masked higher-order harmonics

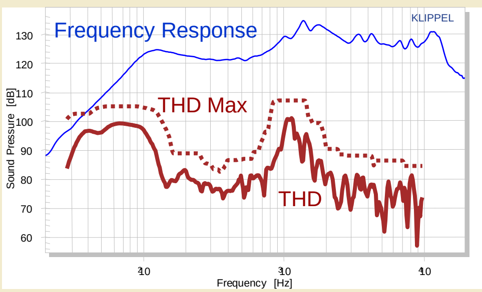
→ Multi-tone distortion is not sensitive for coil rubbing and other defects

Voice Coil Rubbing

Stimulus: sinusoidal sweep



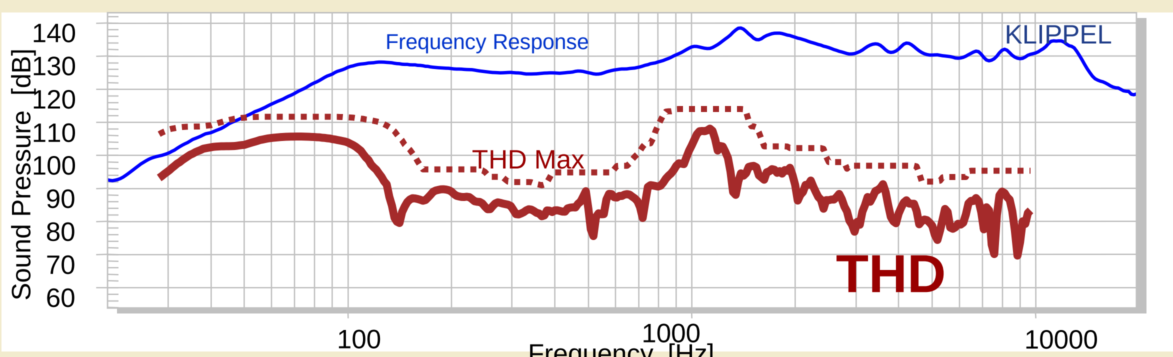
1V



2V

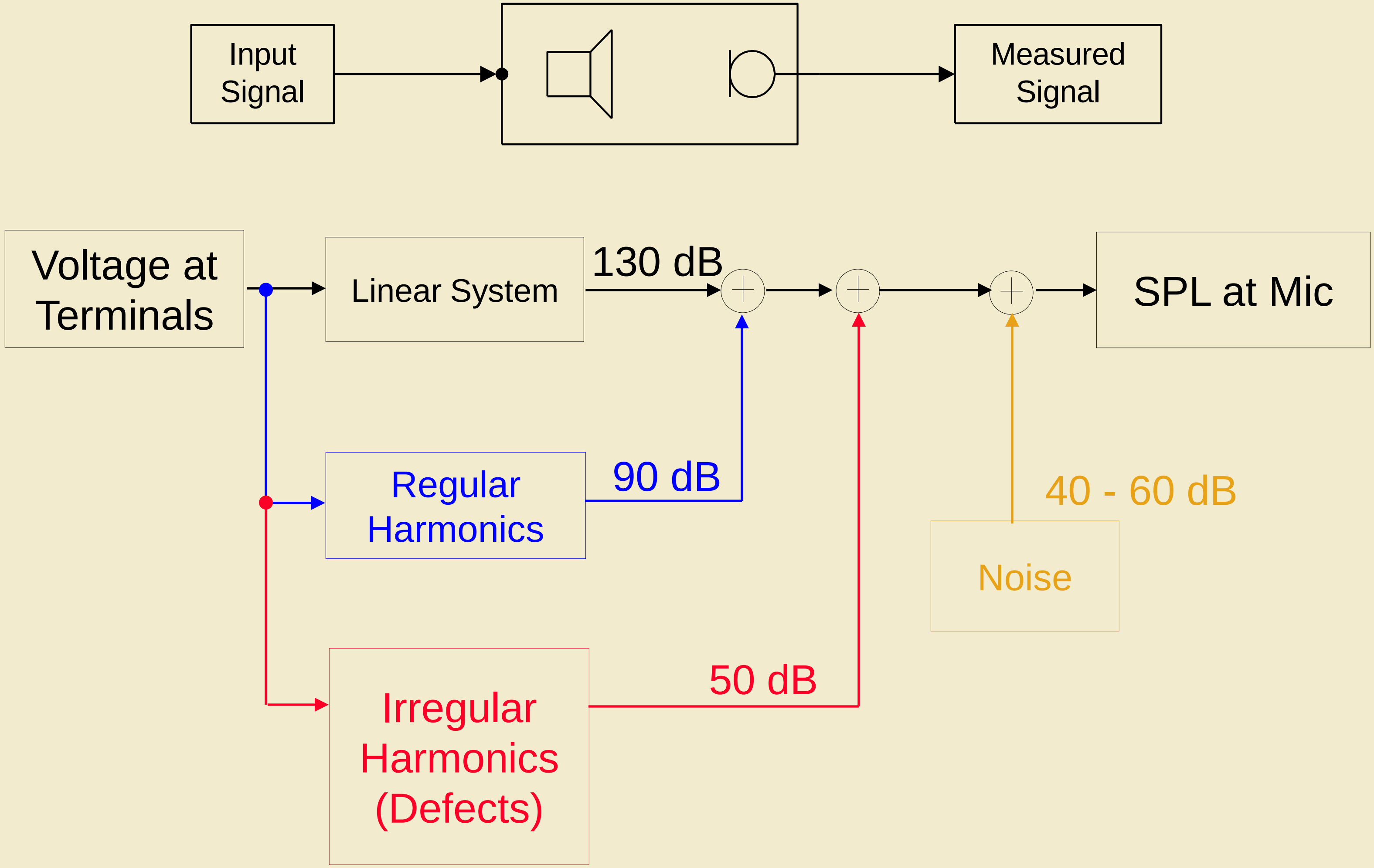
- •THD measures the rms value of all harmonics
- •Regular distortion are dominant
- •Distortion of defects have not much energy

→ THD is not sensitive for coil rubbing and other irregular defects !!



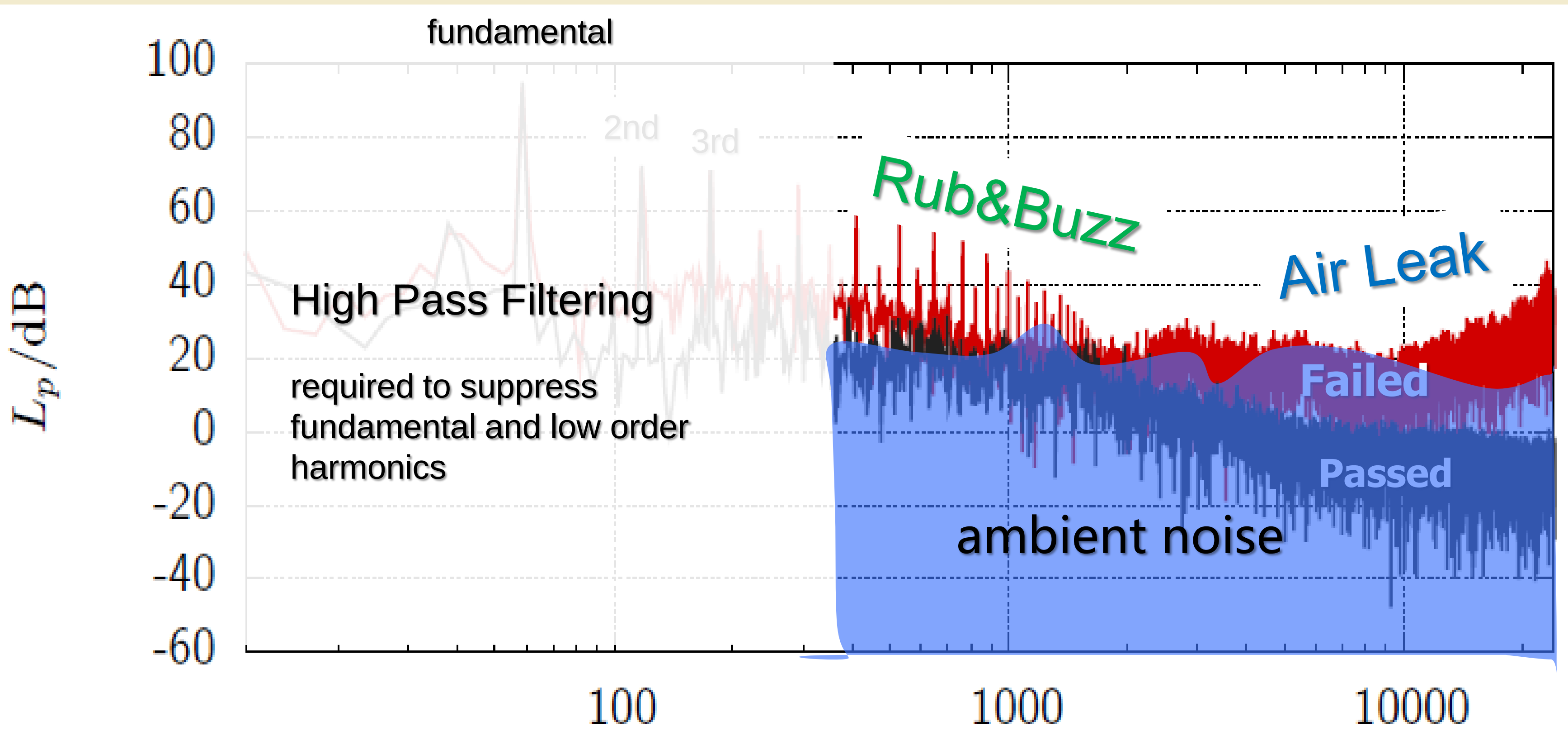
3V

Sound Pressure Level of Signal Components



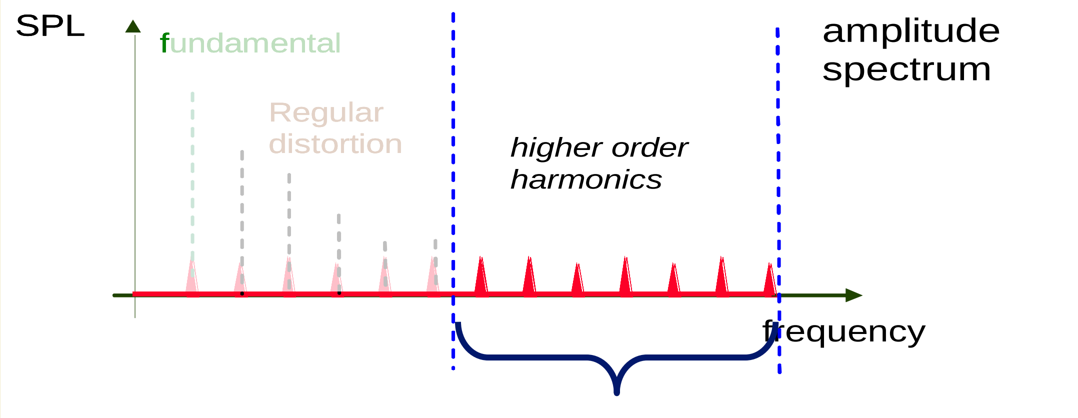
Frequency Domain Analysis

60 Hz Tone reproduced by a good and bad speaker



Simple Approach

exploiting amplitude of higher-order harmonics only

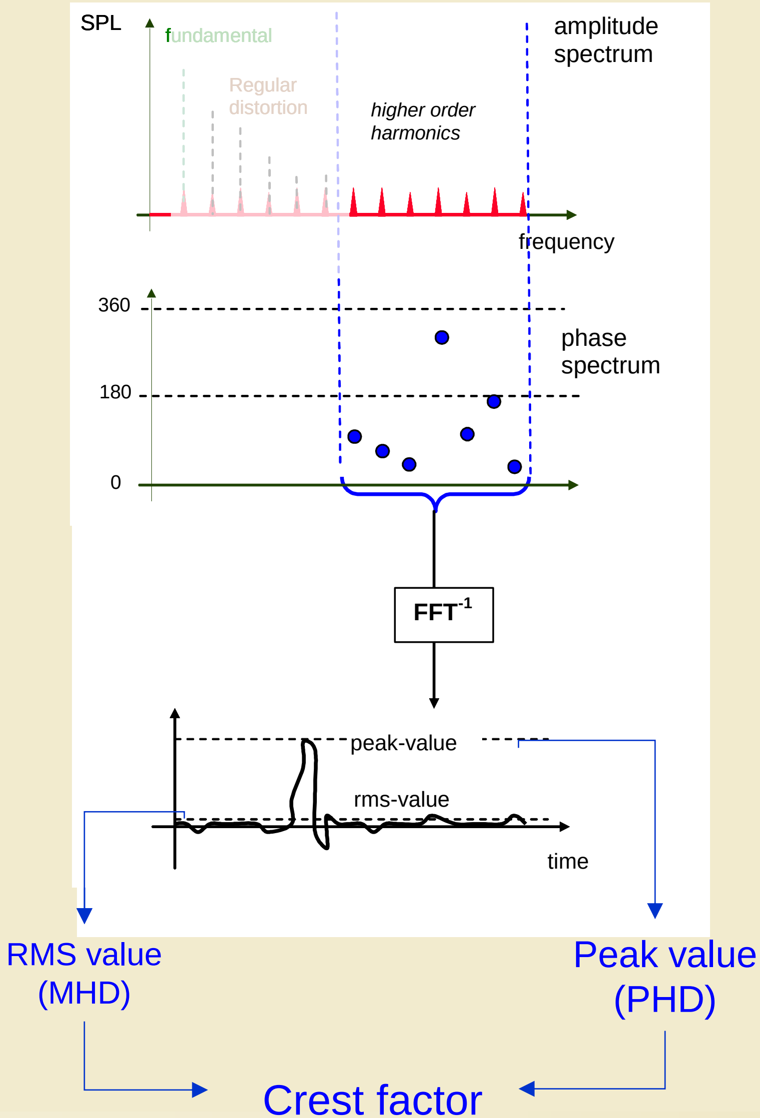


RMS value of Higher-harmonics

PROBLEMS:

- considering deterministic defects only
- each harmonic is close to the noise level
- insensitive to loose particles and air leakage noise

Time Domain Analysis



Solution → back to the time domain

→ exploiting amplitude and phase of higher-harmonics and all non-harmonic components

→ peak value reveals small transients (clicks)

→ Sensitive for all loudspeaker defects

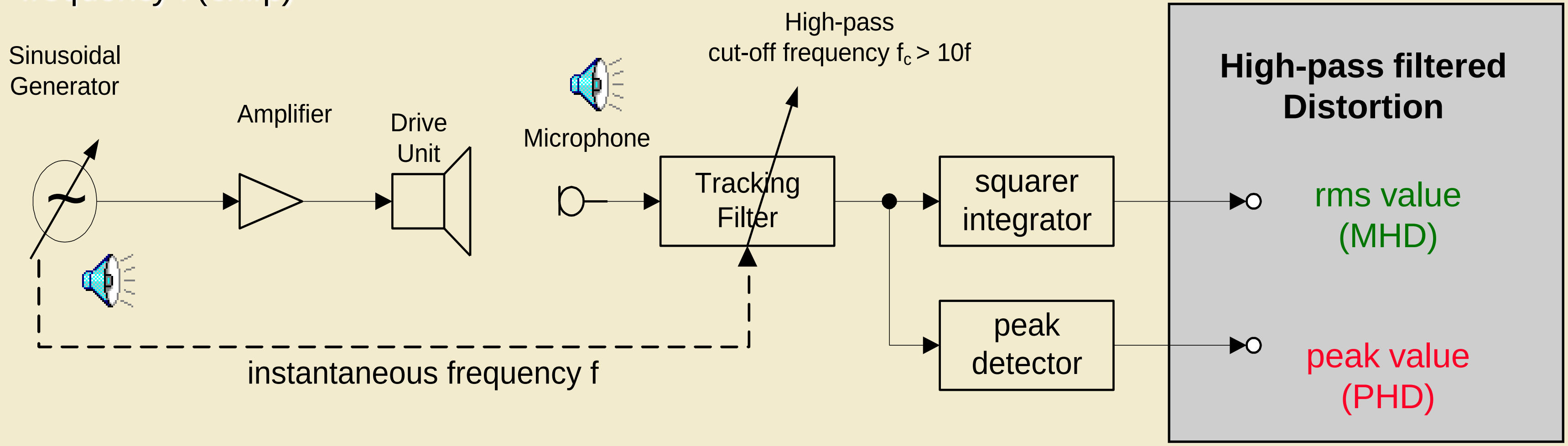
most loudspeaker defects generate symptoms with high crest factor

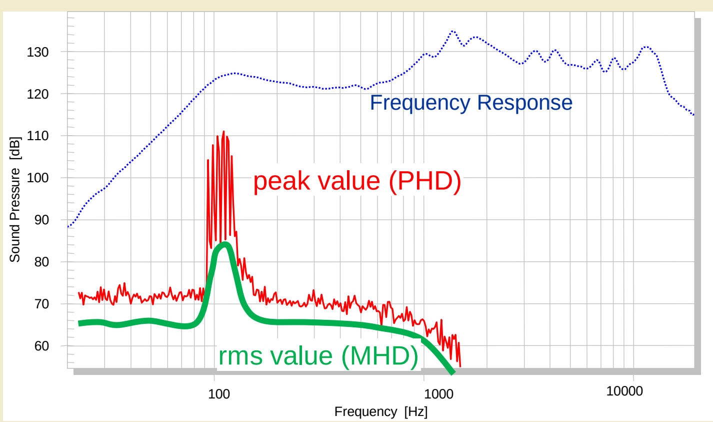
but

regular loudspeaker distortions, electrical and microphone noise have lower crest factor

Peak value Contra rms-Value

Single tone with varying frequency f (chirp)

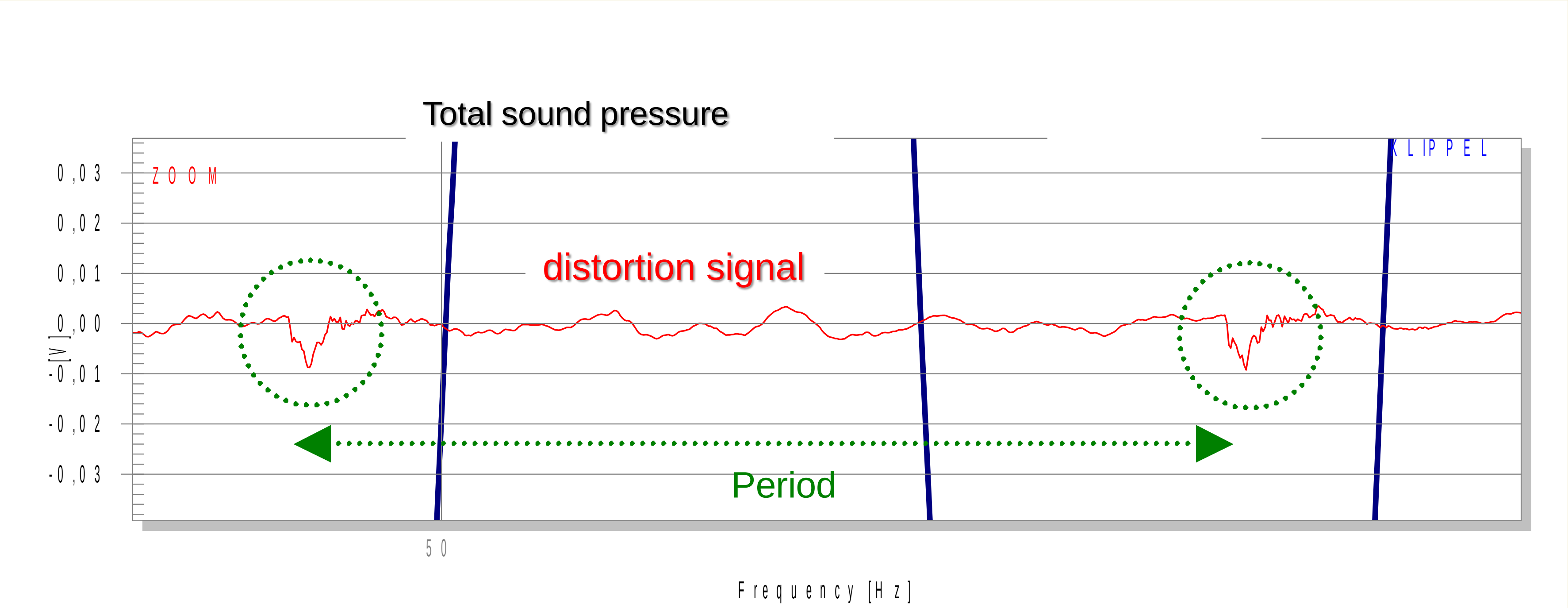




Peak value (PHD) is a sensitive measure for most irregular defects such as „rub and buzz“, loose particles !!

Distortion Signal in the Time Domain

output of the high-pass filter f_c=20f



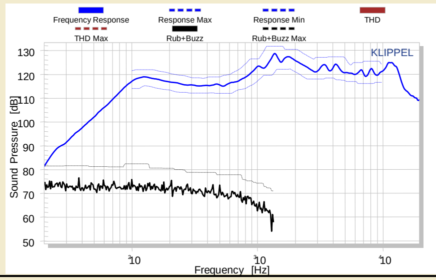
- Regular distortion have high energy
- Disturbances have low energy
- Disturbances are concentrated in time during a period

→ impulsive distortion (high crest factor)

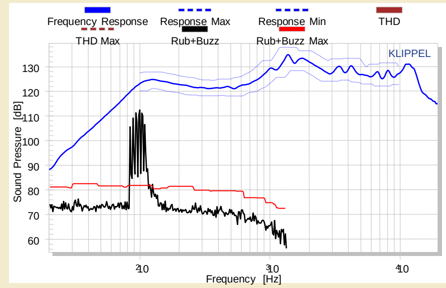
→ Active compensation is useful

Voice Coil Rubbing

Stimulus: sinusoidal sweep

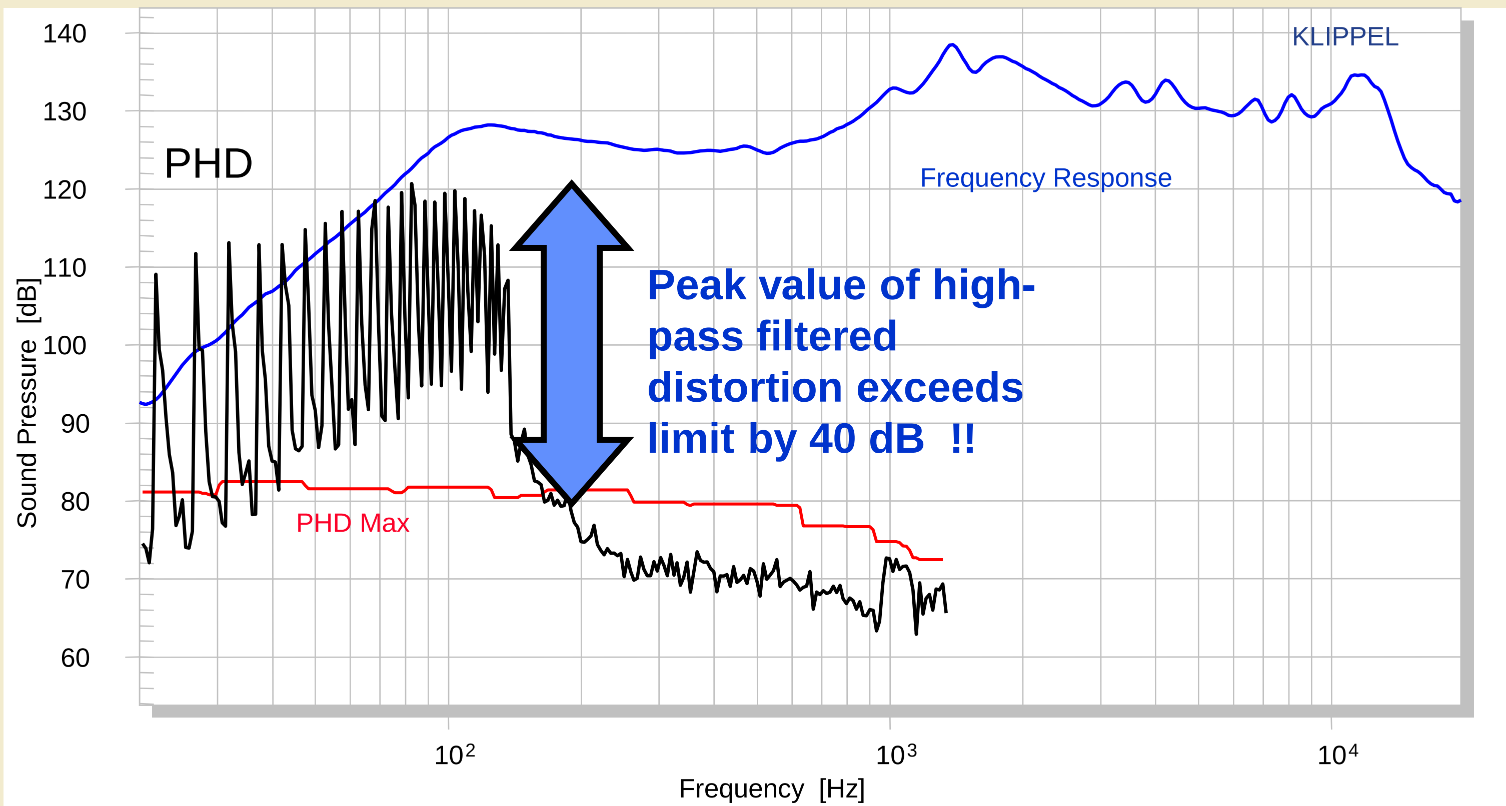


1V



2V

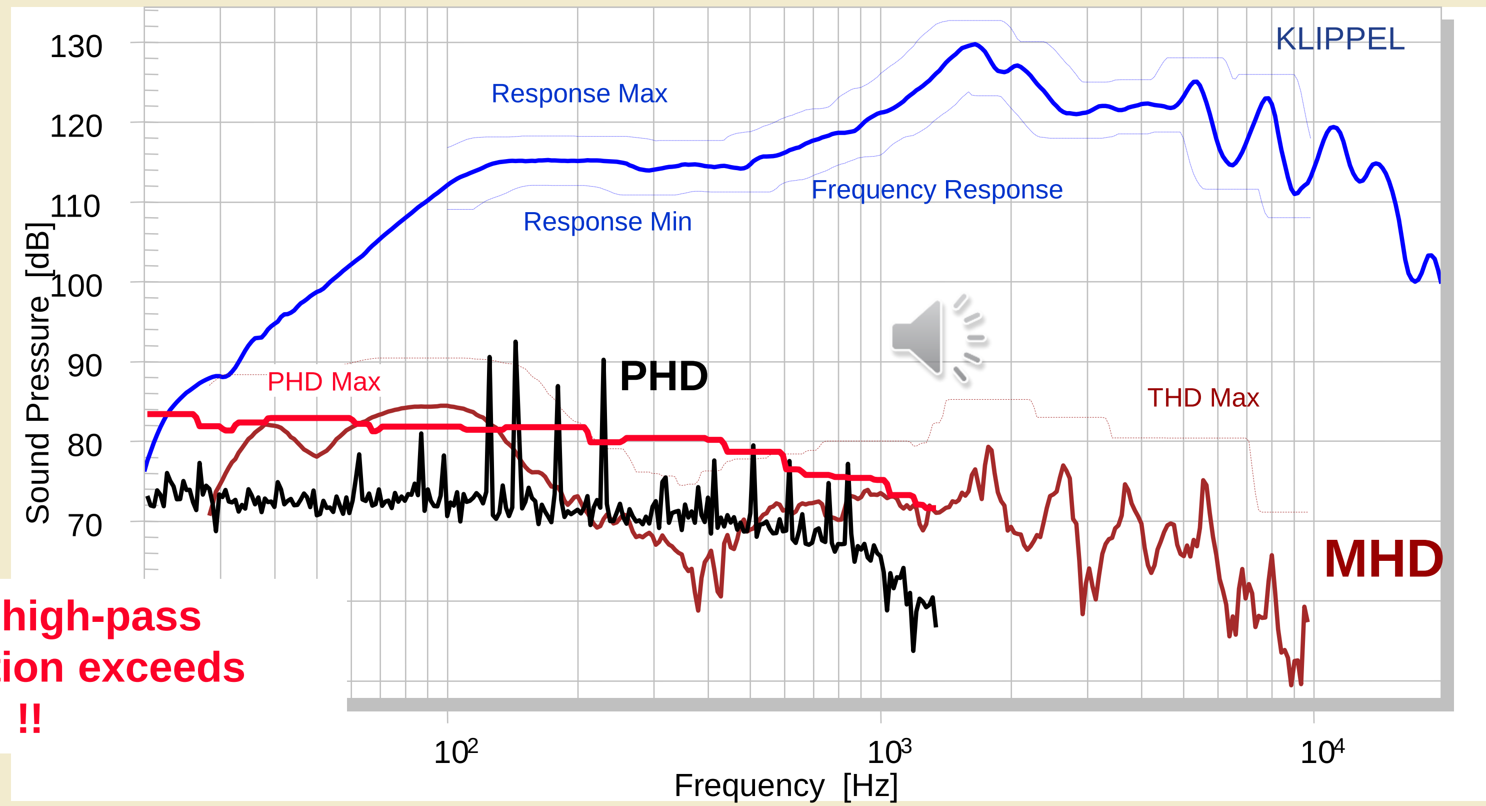
3V



Very Small Loose Particle

one grain of fine salt

Sinusoidal Stimulus



Peak Value of high-pass filtered distortion exceeds limit by 10 dB !!

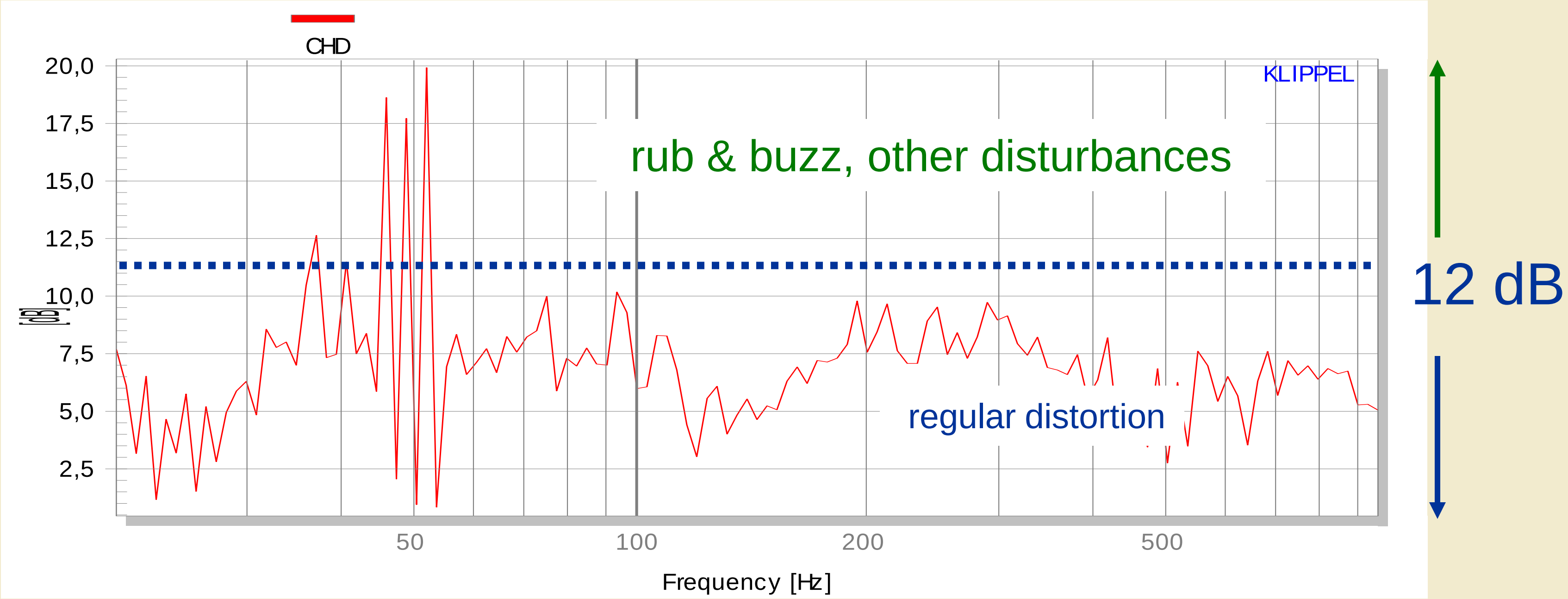
Crest factor of high-pass filtered distortion (CHD)

Stimulus: Sinusoidal sweep

$$CHD(f) = \frac{PHD}{MHD}$$

peak-value within one period

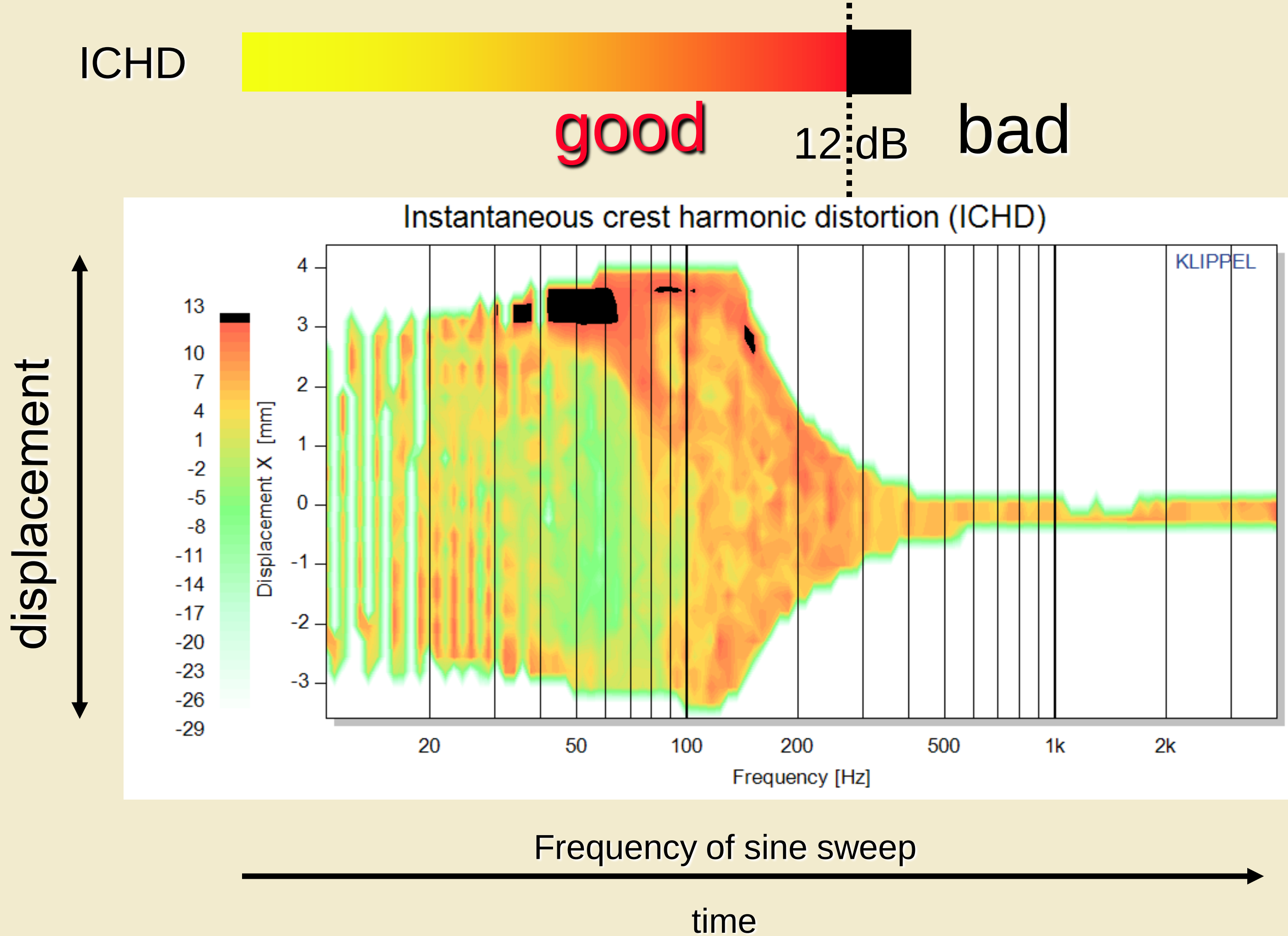
Rms-value averaged over one period



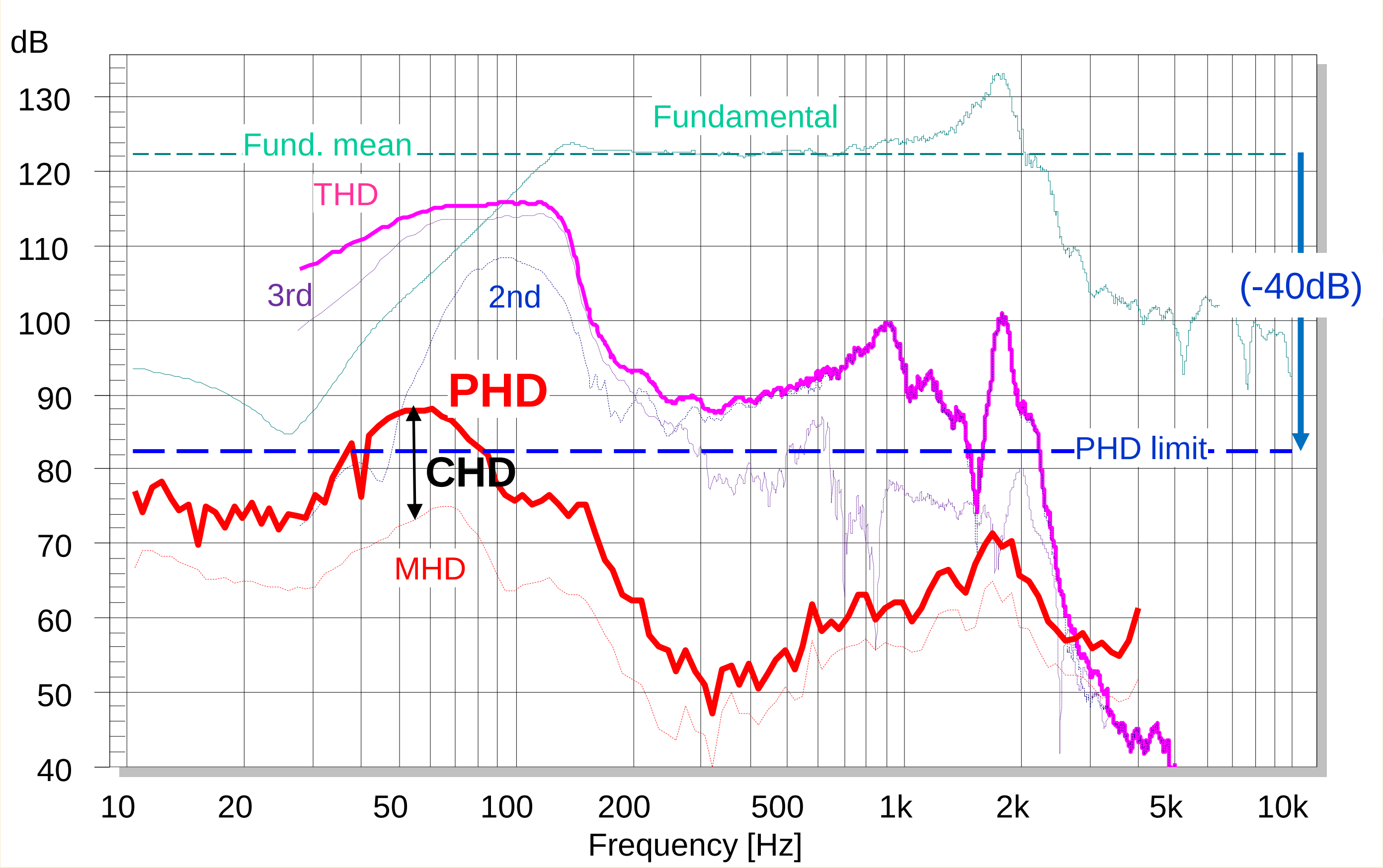
CHD can be interpreted on an <u>absolute</u> scale !

CHD expoits the phase information of all high frequency components

Instantaneous crest factor of high-pass filtered distortion ICHD(f,x)



Loudspeaker Defect or Noise ?



is not an audibility threshold !

Symptoms of a significant defect:

1. Sufficient amplitude: peak value $PHD > FUND_{mean} - 40dB$

2. Impulsive: crest factor $CHD > 12dB$

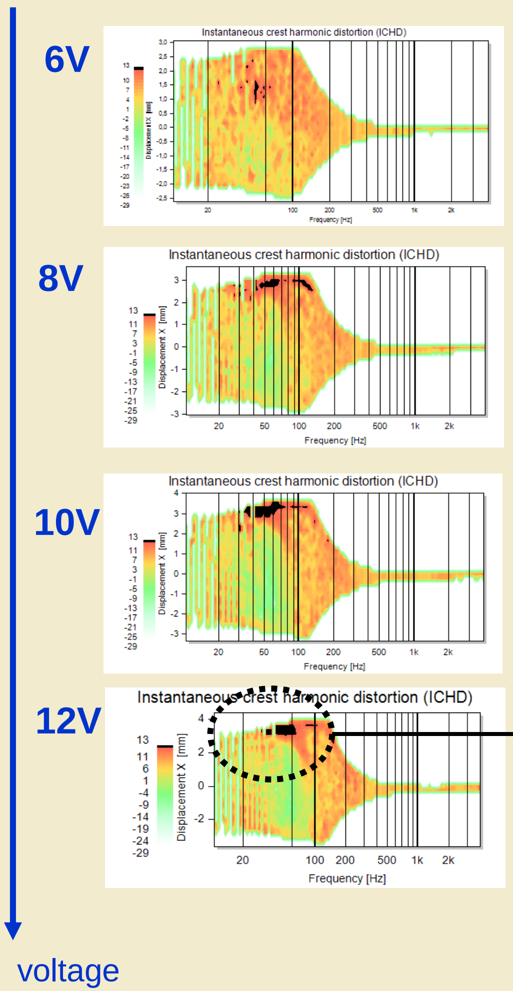
Check for coincidence !

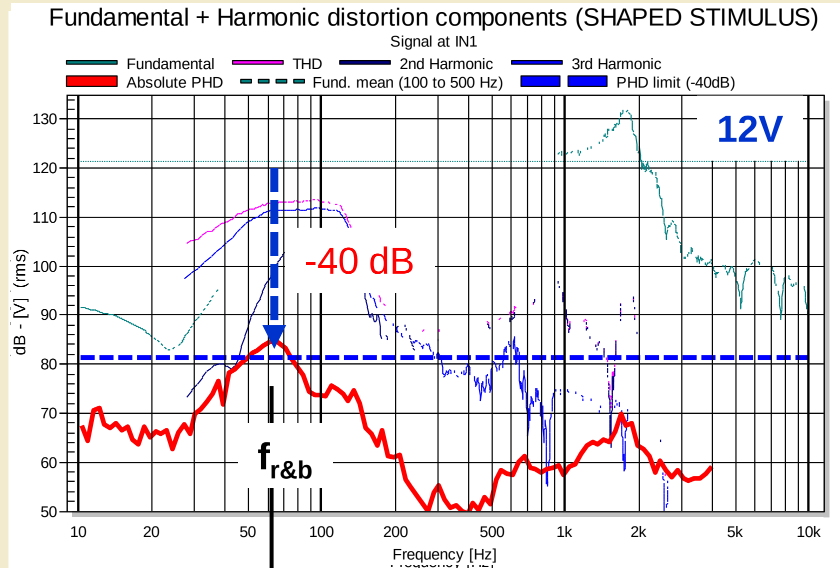
(microphone noise is not impulsive)

Characteristics for Diagnostics

Single-valued parameter derived from PHD and CHD

Batch of TRF measurements





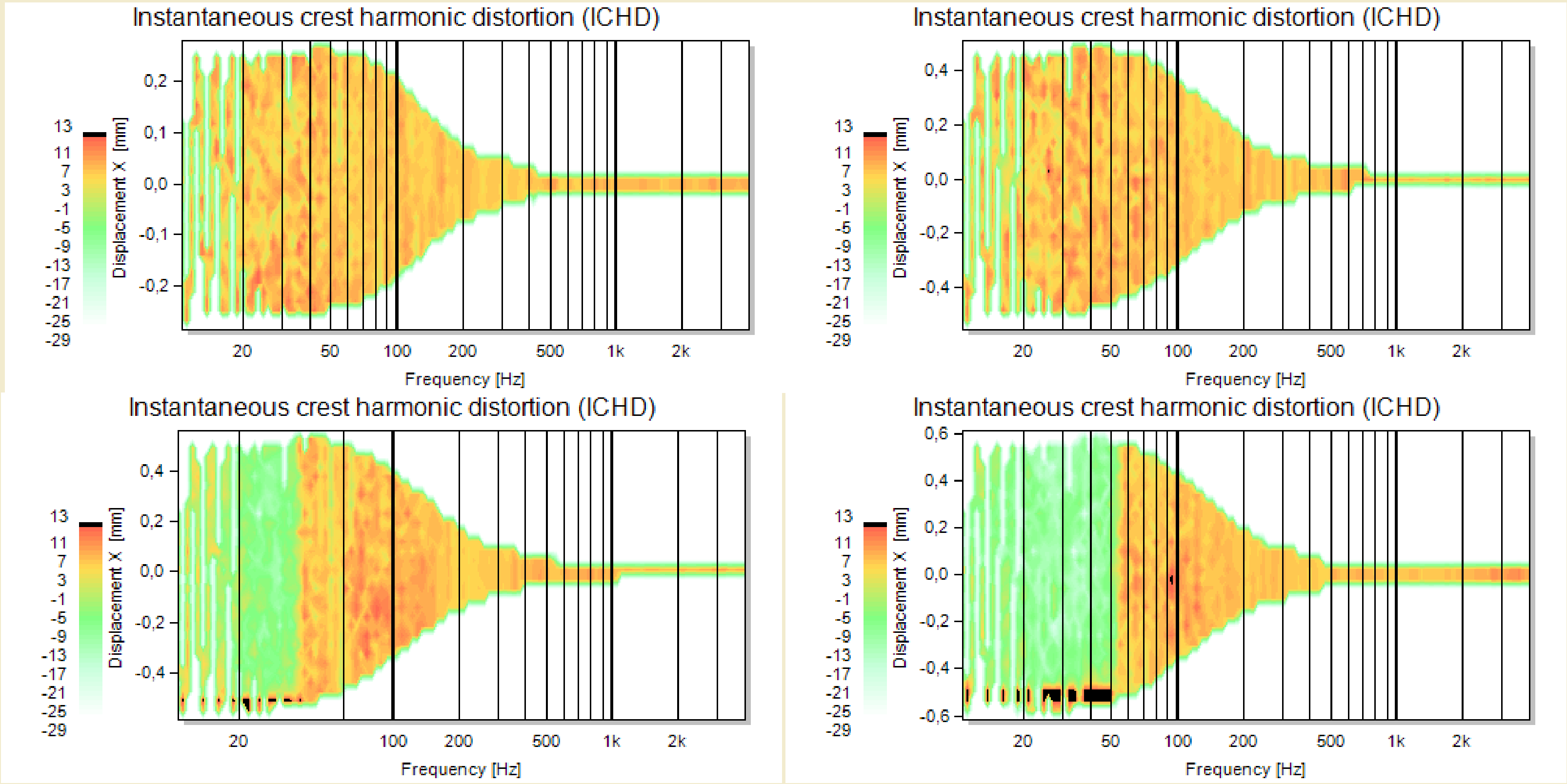
PHD > FUND$_{mean}$ - 40dB
high amplitude

CHD > 12dB
impulsive

Significant defect (R&B)

Conditions:
Rms Voltage $U_{r\&b}$ = 12 V
Peak displacement $X_{r\&b}$ = 4mm
Frequency $f_{r\&b}$ = 65 Hz
Inst. Displacement $x_{in,\ r\&b}$ = 3.8 mm

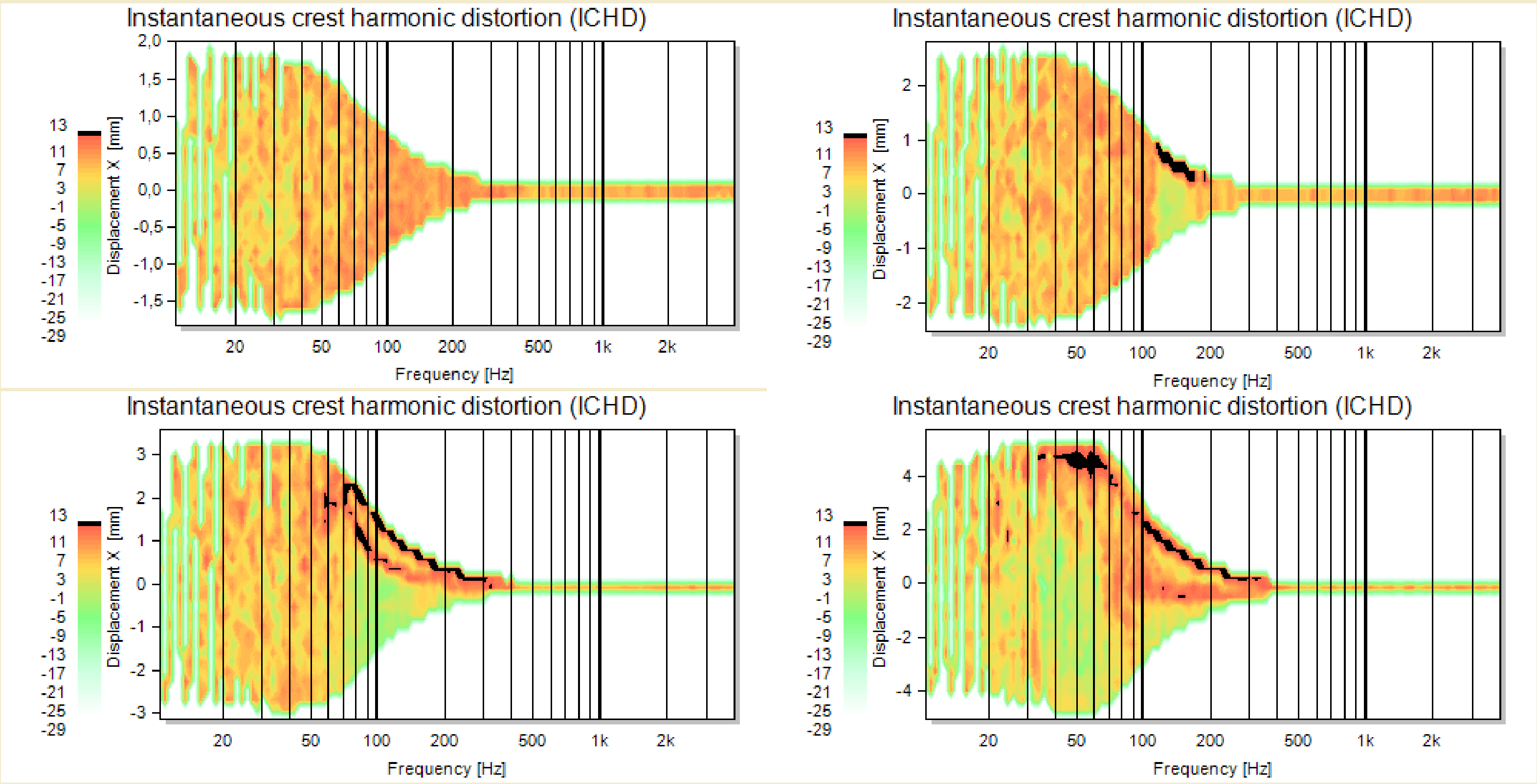
Diagnostics on Irregular Defect (1st example)



Conditions:
• Positive peak displacement at 0.5 mm below f_s
• above a terminal voltage of 0.9 V

Root Cause: Bottoming

Diagnostics on Irregular Defect (2nd example)



Conditions:

- Negative turning point of voice coil excursion above f_s
- maximal acceleration → Tilting of voice coil former
- independent of displacement

⇨ **Root Cause: Voice coil Rubbing**

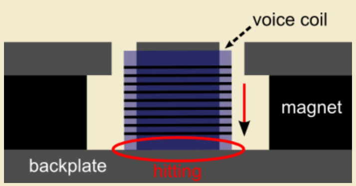
Clues for Diagnostics of Defects

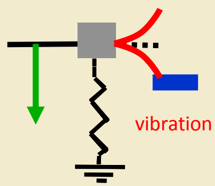
derived from ICHD(f,u) measured versus frequency f and voltage u

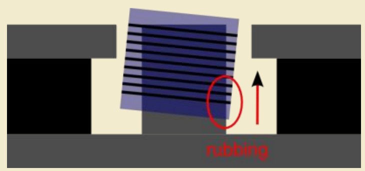
- **Coil rubbing** initiated by a tilting of the voice coil former occurs at maximal acceleration corresponding with the positive and negative maxima of the displacement. This occurs usually at frequencies above resonance where the acceleration is maximal while the amplitude of the displacement decreases. When the voltage is increased the coil rubbing will also occur at the turning points of the voice coil at higher displacement values.
- **Buzzing part** generates high ICHD for particular (reproducible) values of frequencies and displacement because it behaves like a coupled nonlinear resonator. Above a critical voltage when it starts this defect is almost independent on the peak displacement.
- ***Coil bottoming*** at the rear plate generates high ICHD at a clearly defined negative displacement independent of frequency. Increasing the voltage of the excitation the maximal negative displacement is constant but the loudspeaker generates a dc displacement shifting the coil in the opposite direction.
- ***Limiting surround*** generates high ICHD at maximal positive or negative displacement independent of the excitation frequency. The instantaneous displacement where ICHD > 12 dB raises by increasing the voltage because the suspension behaves not as a hard limiting nonlinearity like *coil bottoming*.
- ***Tensile slap*** generates a high value of ICHD at reproducible values of displacement and frequency because the wire behaves as a coupled mechanical system having its own vibration mode and natural frequency.
- ***Air leakage*** in a dust cap generates a high ICHD for frequencies below resonance f< fs where the sound pressure of the enclosed air is high.
- ***Loose particles*** generate ICHD > 12 dB at random values of frequencies and instantaneous displacement.

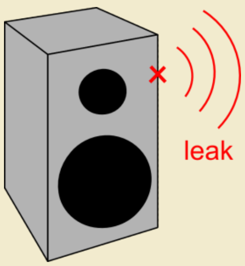
Basic Classification of Loudspeaker Defects

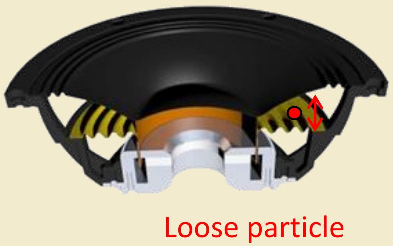
Coil hitting backplate	Buzzing loose joint	Rubbing voice coil	Flow noise at air leak	Loose particle hitting membrane







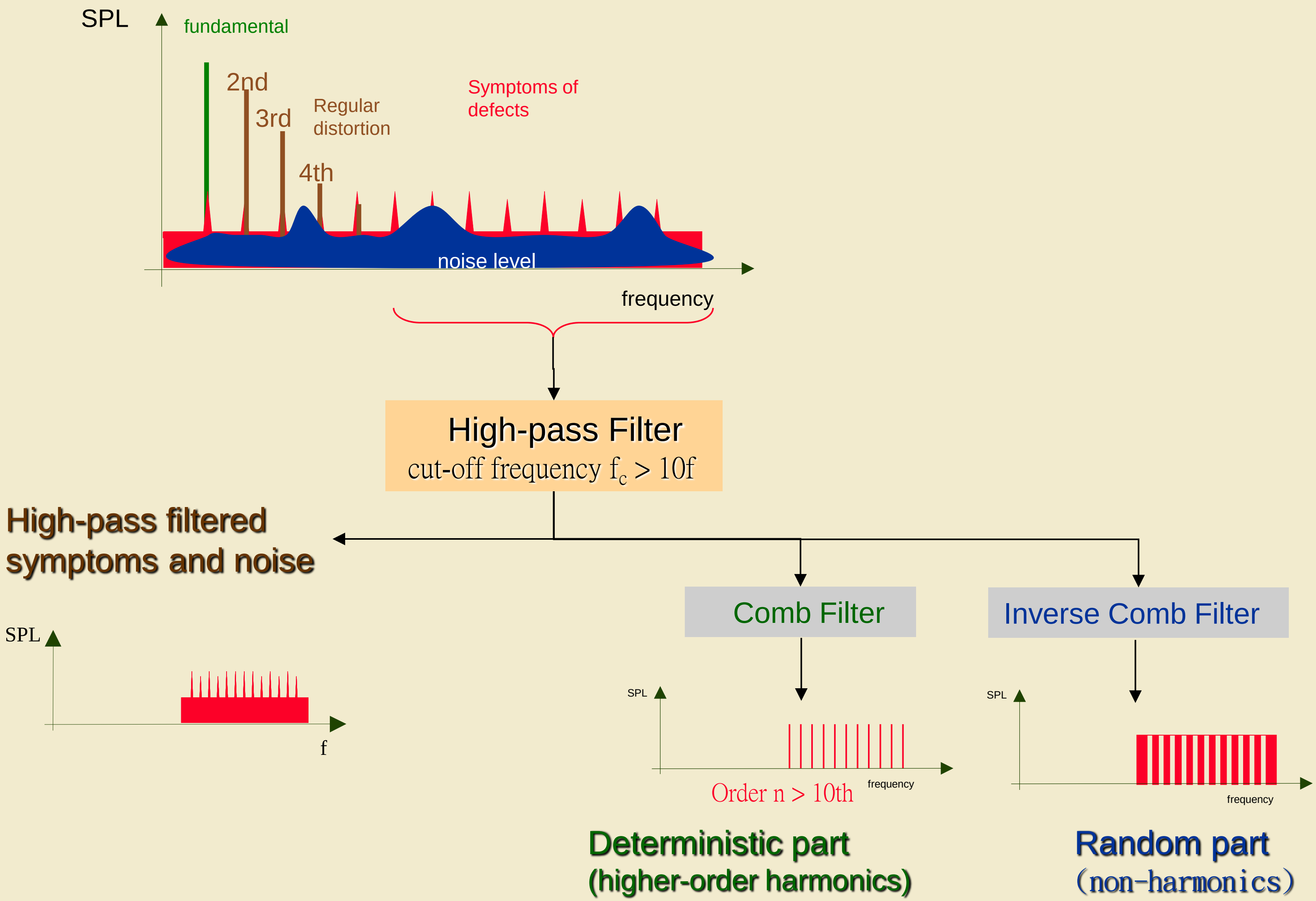




Deterministic — **Semi-random (mixed characteristic)** — **Random**

Deterministic	Semi-random (mixed characteristic)	Random
Waveform is completely reproducible	Envelope is reproducible (Waveform is not)	Waveform is not reproducible

Exploiting all Symptoms of the Defect

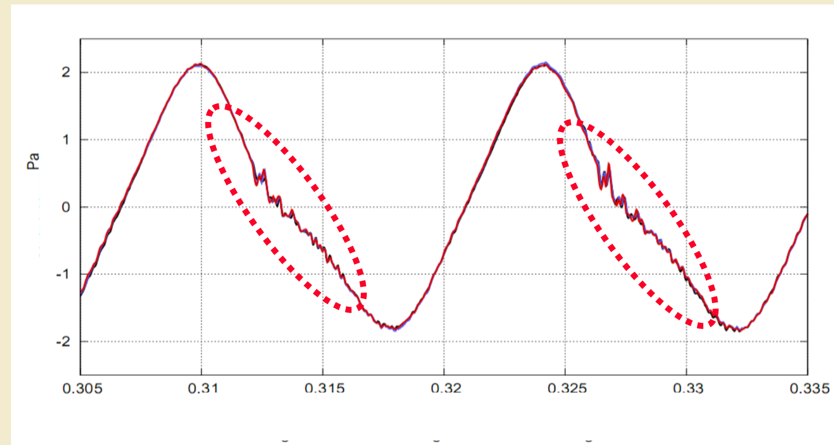


Deterministic Distortion

Results of three measurements

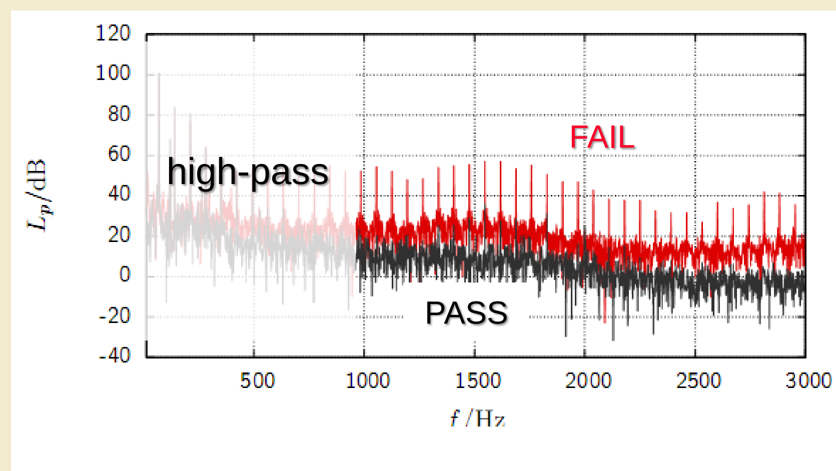
Example:

tensile slap, bottoming

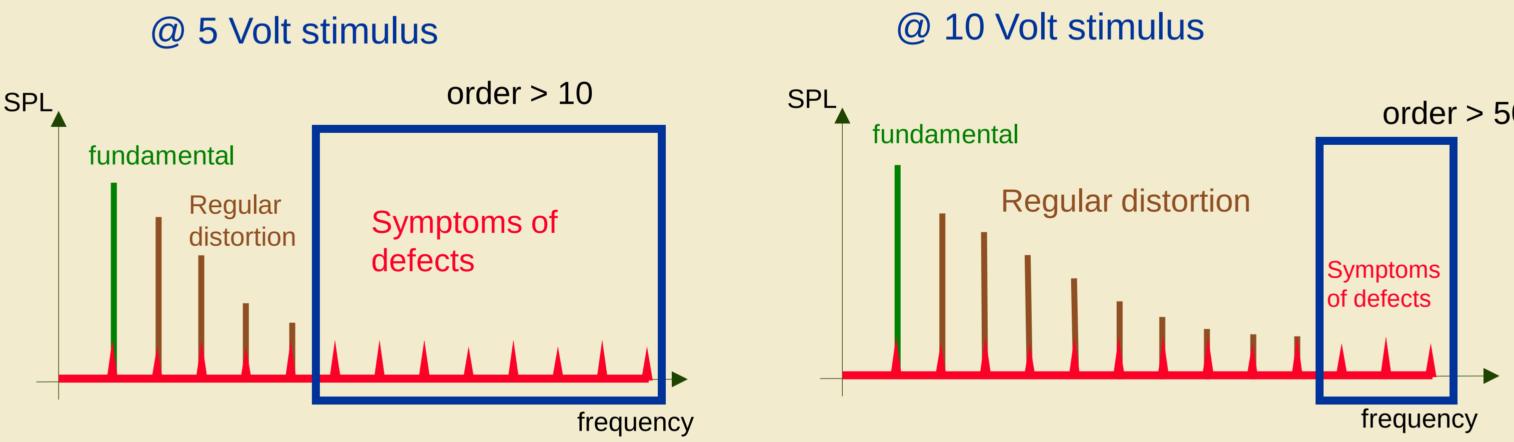


Symptoms:

- Reproducible, repeatable
- Related with stimulus
- impulsive distortion
- Deterministic amplitude and phase of higher-order ha



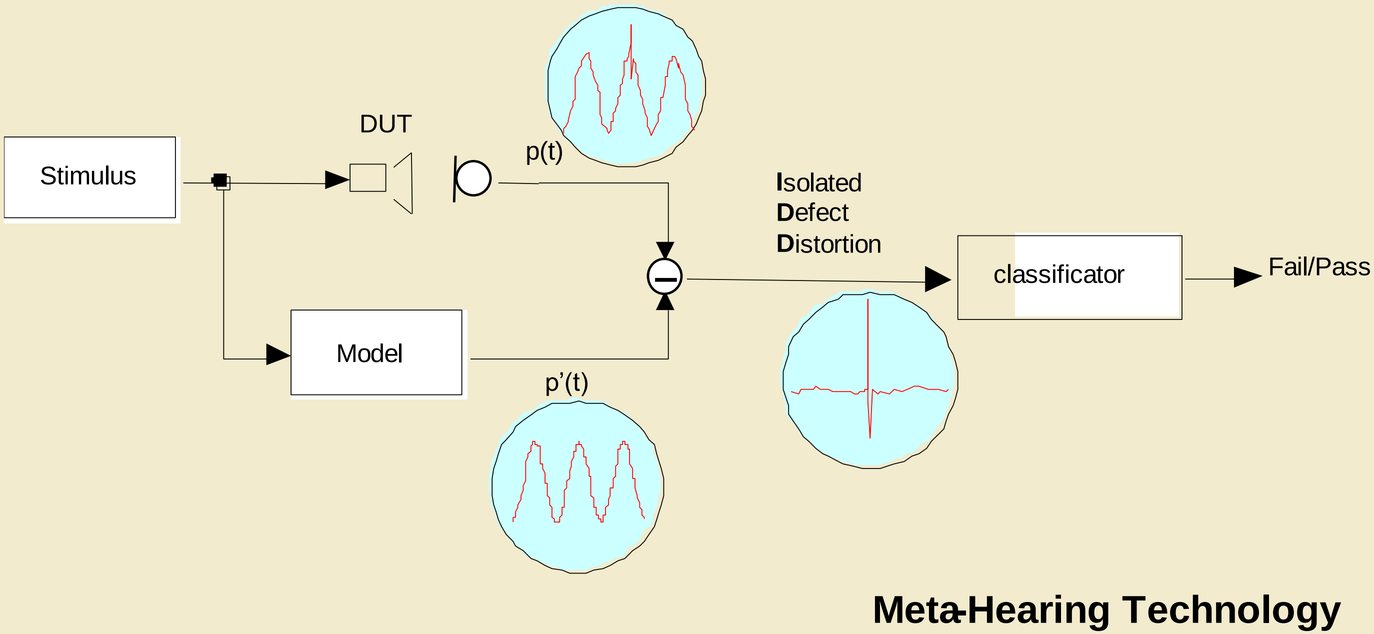
Defects Masked by Regular Nonlinearities



Where are the limits of a human tester ?

- Symptoms of some defects have almost constant energy
- Distortion of regular nonlinearities rise with amplitude
- Defects are masked (become inaudible at higher amplitudes)
- Increasing high-pass frequency → less energy → noise problems

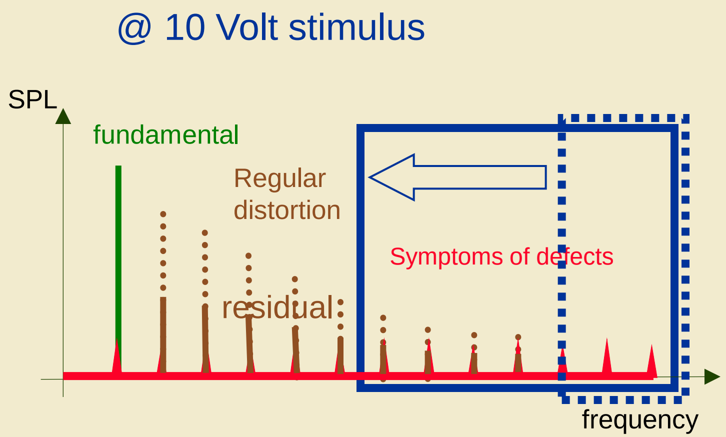
Solution: Active Compensation



- Regular distortion are deterministic and predictable
- Modeling of regular distortion (adaptive learning)
- Masking by regular distortion can be removed actively

→ active compensation

Meta-Hearing Technology

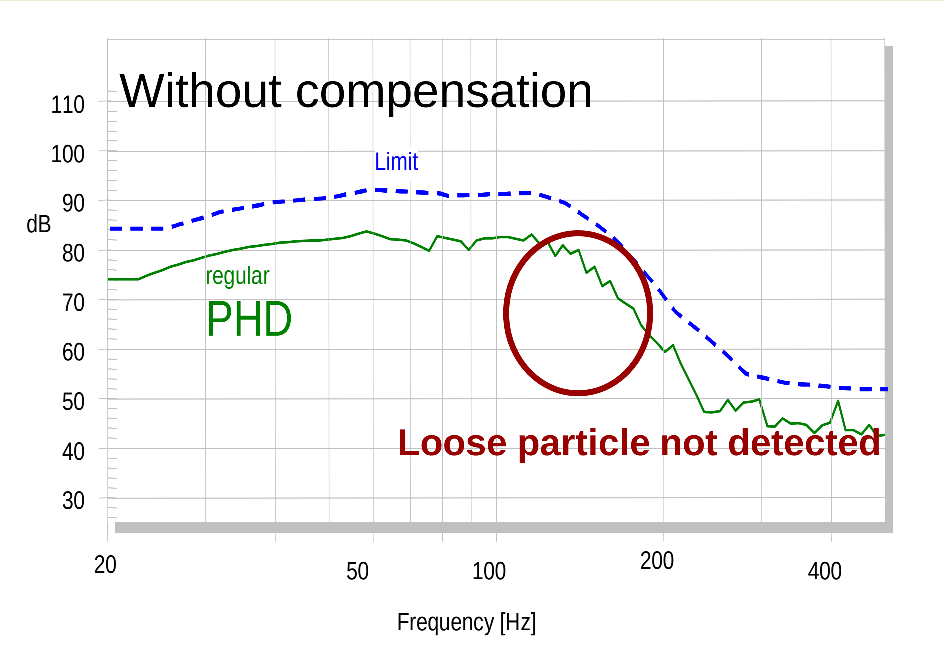


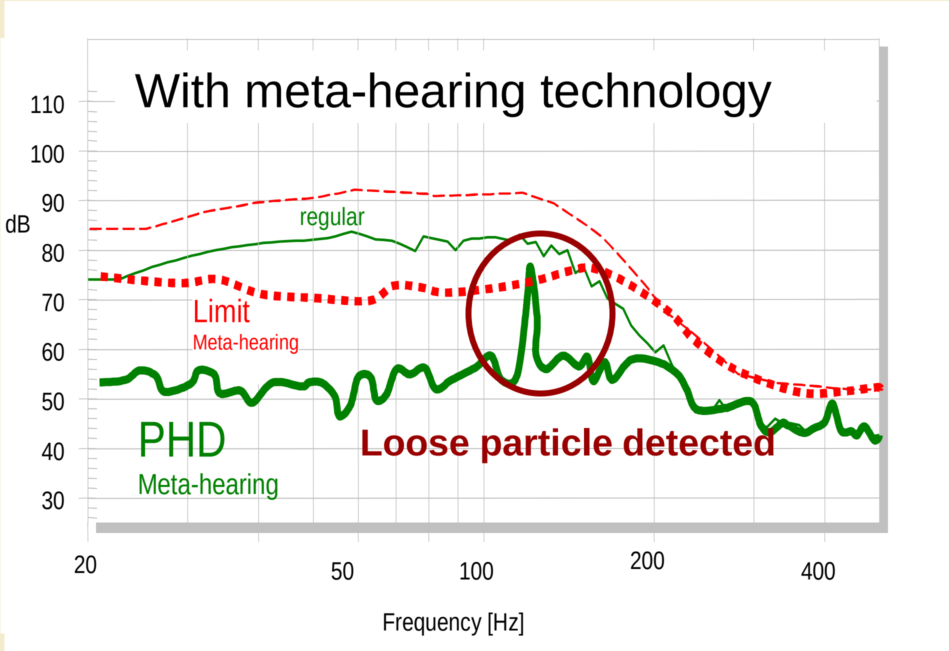
More energy can be used !

- Exploiting symptoms masked by regular distortion
- Test of driver at maximal amplitude becomes possible
- Detection of defects with low energy (loose particles)
- Detect failures even if they are inaudible

  (getting worse in final application)

Benefits of Active Compensation





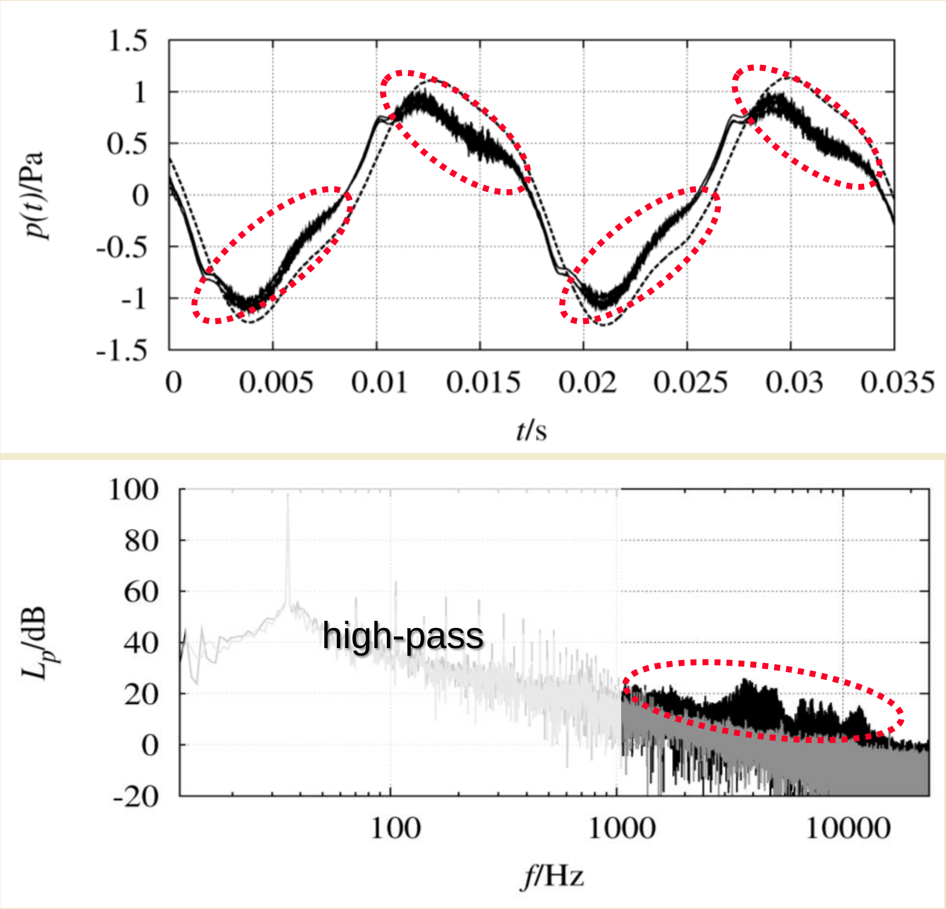
→ Simple definition of PASS / FAIL thresholds

→ Measurement below the hearing threshold

Semi-Random Distortion

Example:

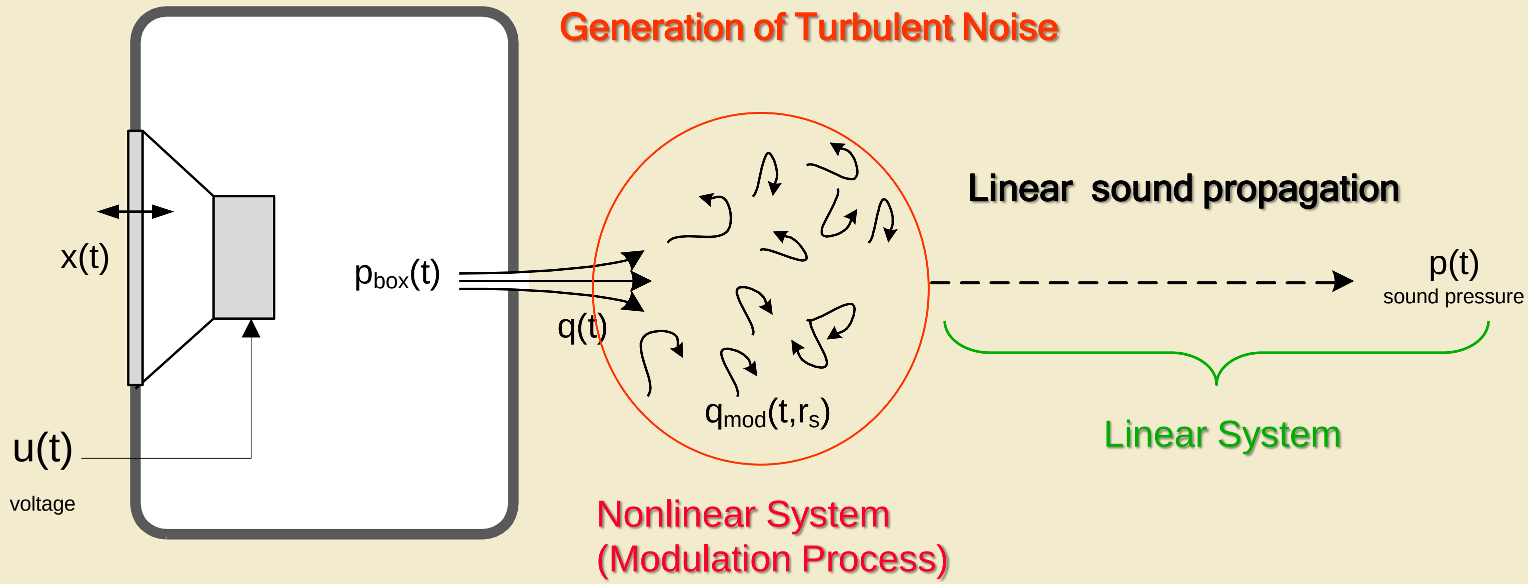
Turbulent air noise generated at leaks, coil rubbing



Symptoms:

- Distortion are NOT reproducible
- Distortion occur at particular times
- Dense spectrum (cover audio band and beyond)

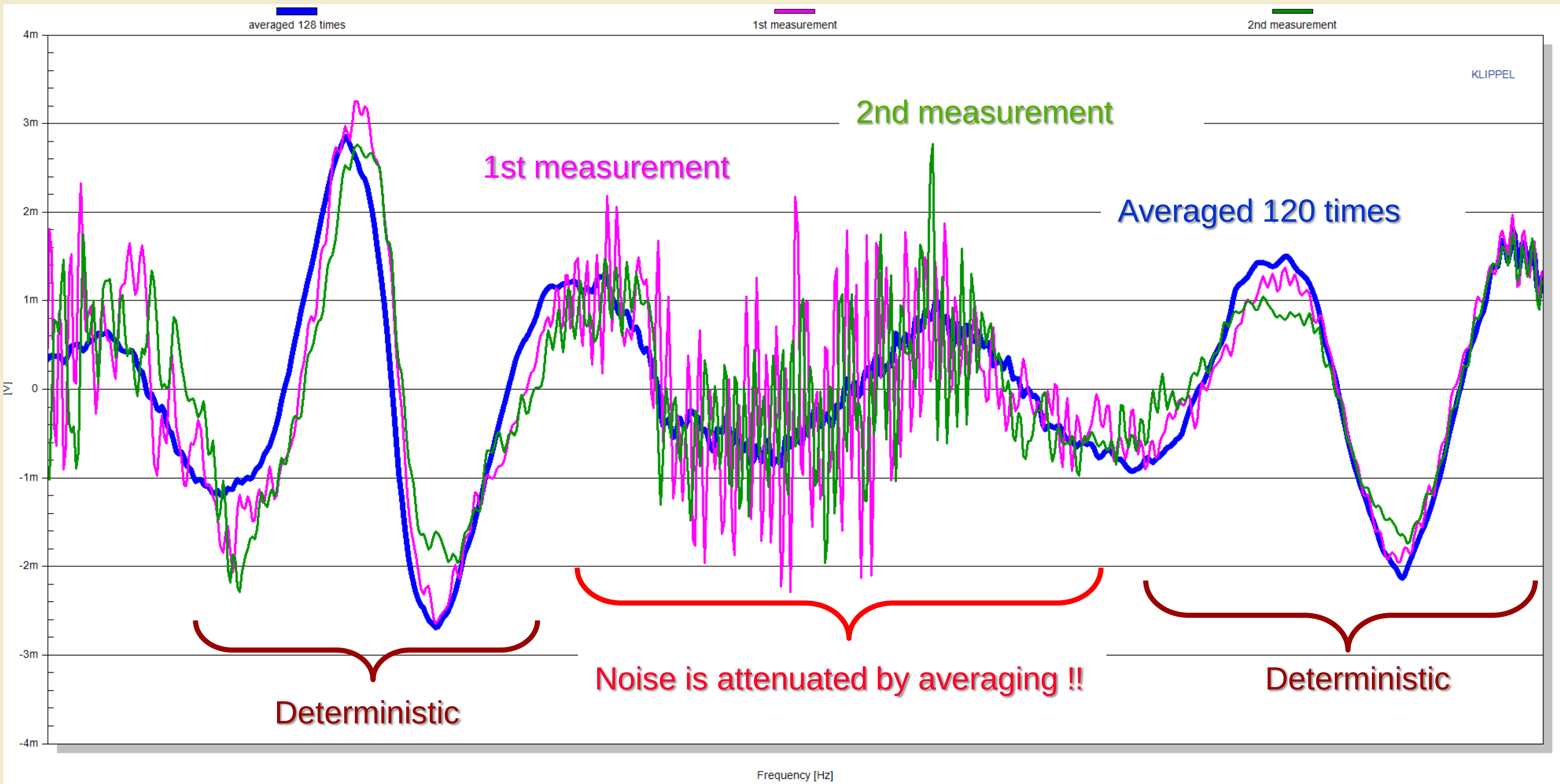
Generation of Turbulent Air Distortion



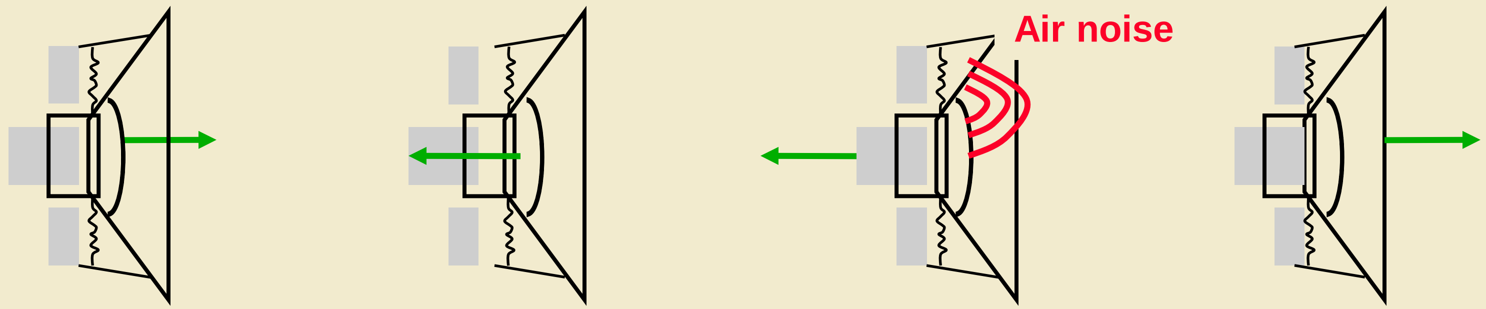
Generation of High Volume velocity q(t)
Voltage → displacement → sound pressure → volume velocity

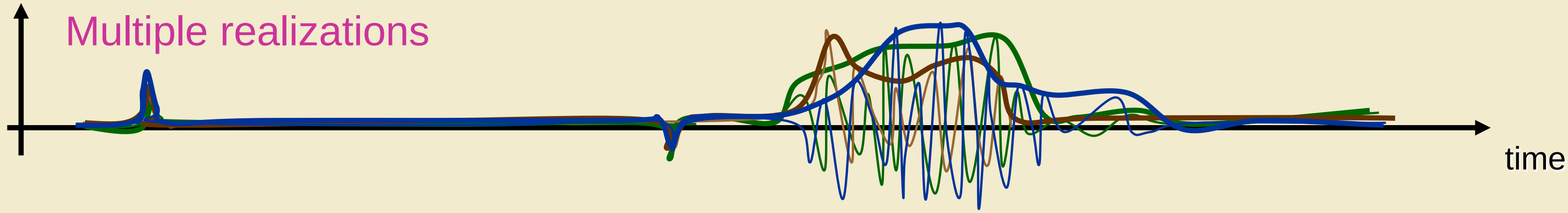
Linear System

Why Are Traditional Measurements Not Sensitive for Air Leaks ?

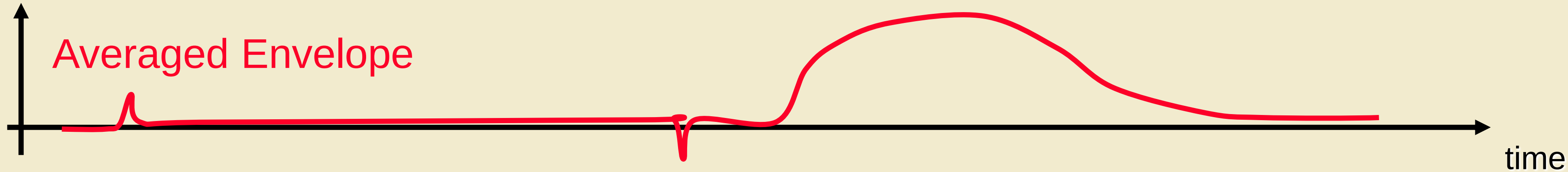


Envelope of the Modulated Noise



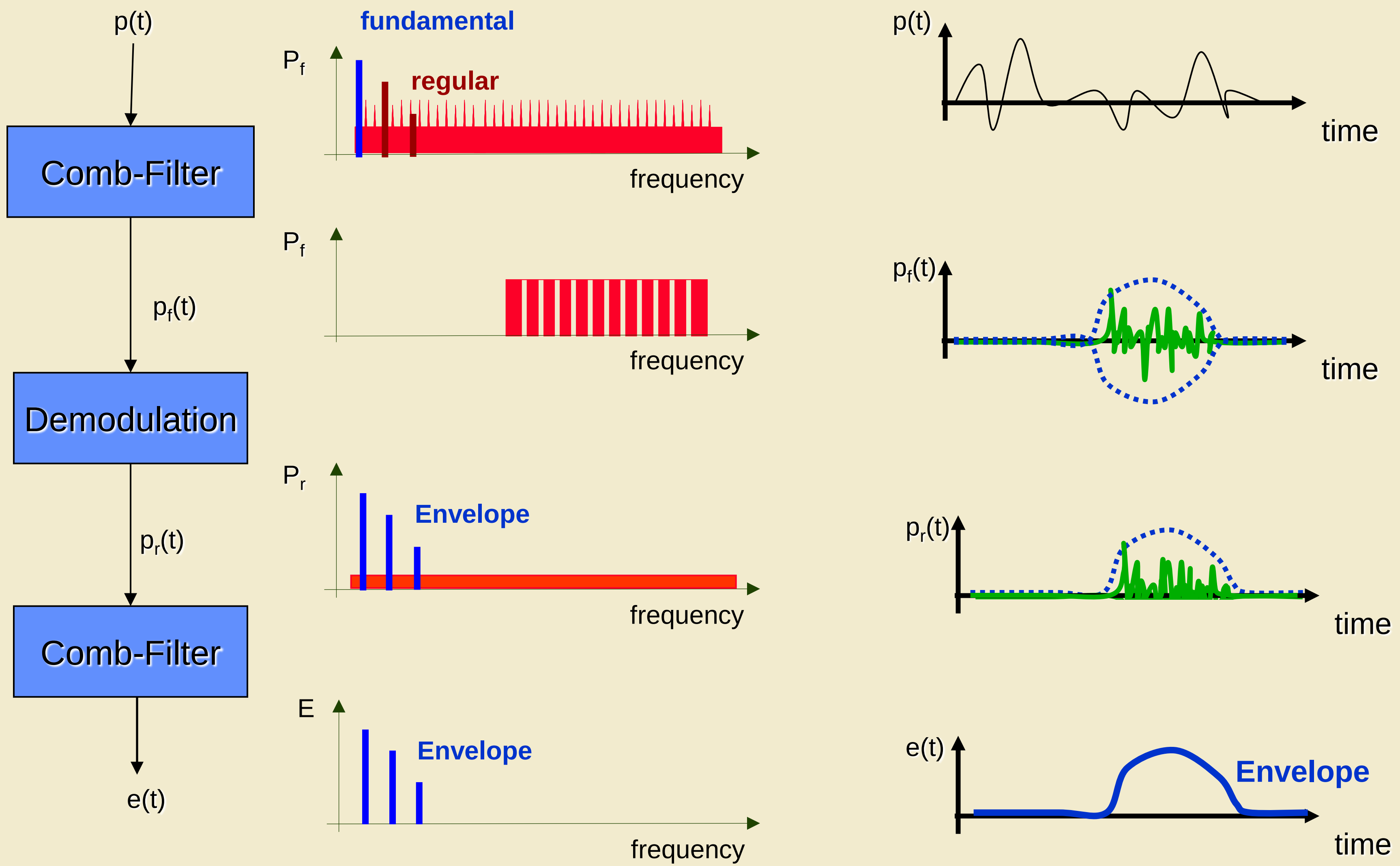


- Envelope of the modulated noise is deterministic
- Averaging of the envelope increases signal to noise ratio



How to Calculate the Envelope ?

Single tone



Absolute Modulation Level

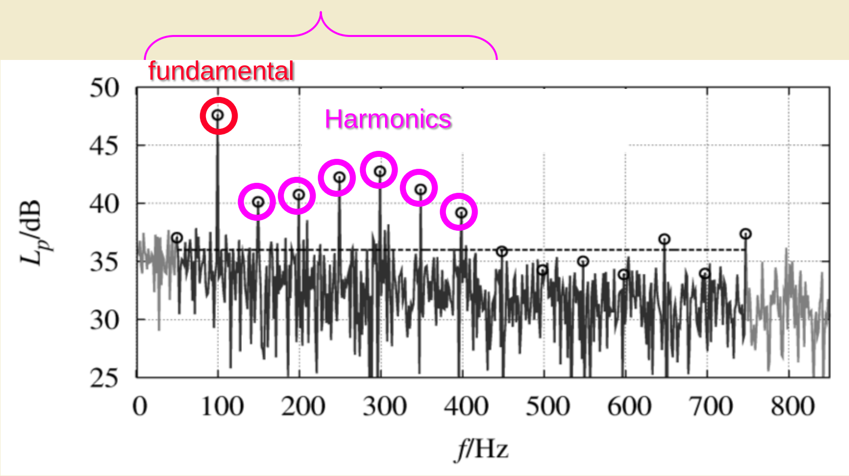
Peak value of the envelope

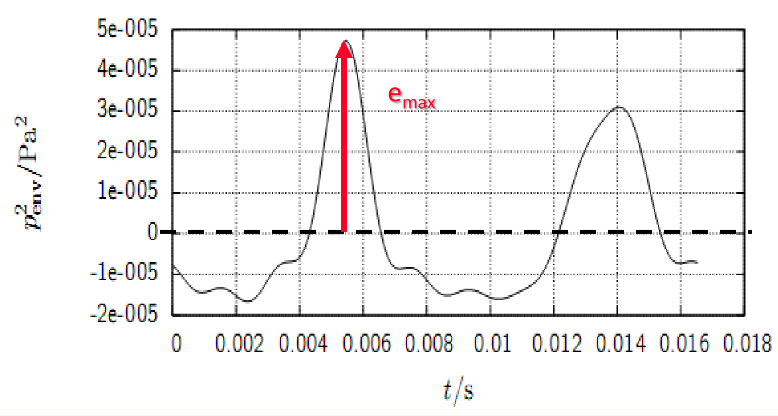
$$MOD_{abs} = 10\lg\left(\frac{e_{max}}{2p_0^{\ 2}}\right)$$

Absolute hearing threshold p_0

- **Shows the peak value of the envelope**
- **is in dB referred to the absolute hearing threshold p_0**
- **good for PASS/FAIL decisions**

deterministic components





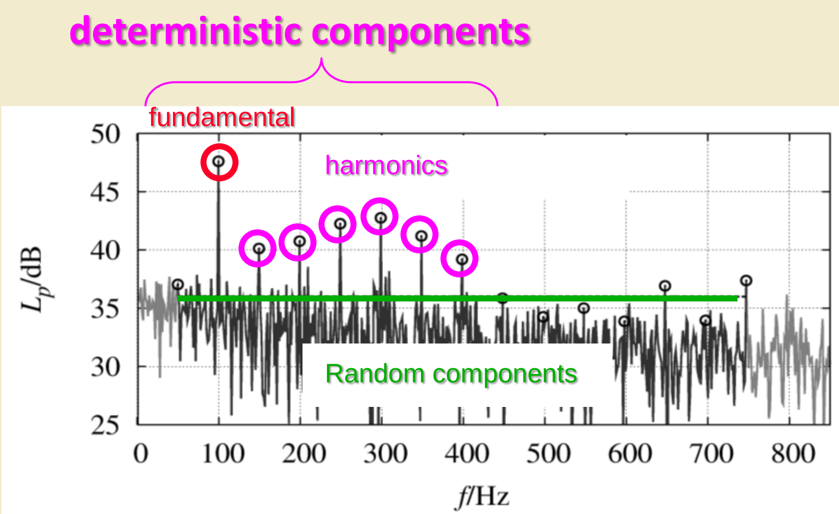
Relative Modulation Level

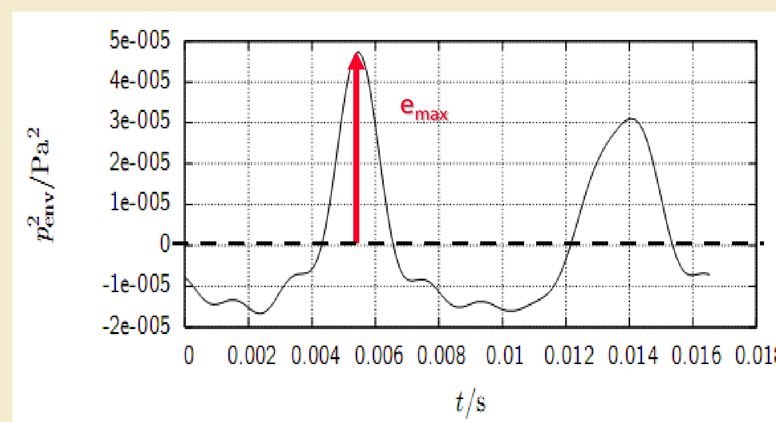
Peak value of deterministic part

$$\mathrm{MOD}_{rel} = 10 \lg \left(\frac{e_{max}}{\tilde{r}^2} \right)$$

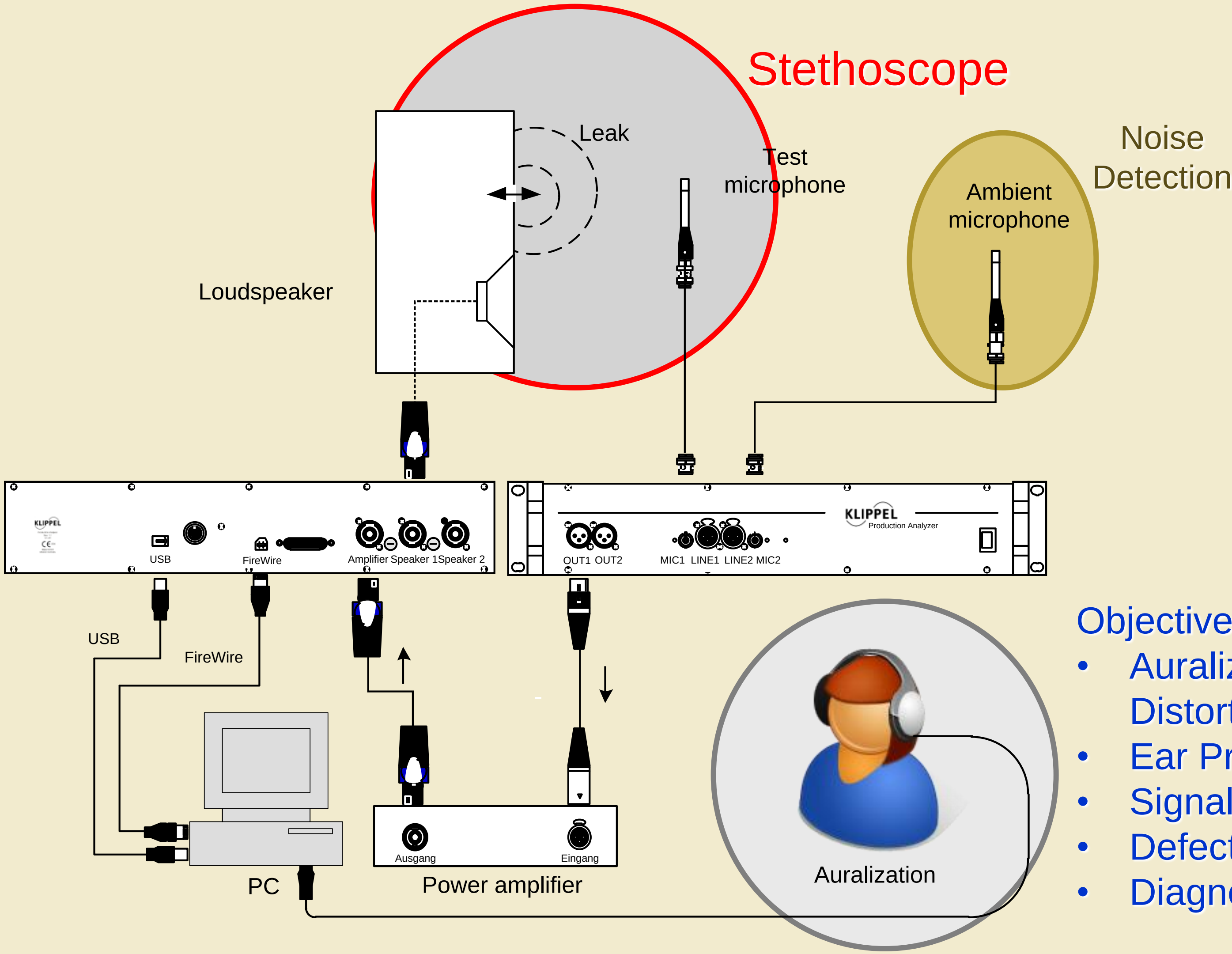
Rms value of random components

- **Considers the ratio of deterministic and random parts of the envelope**
- **Shows significant modulation ($\mathrm{MOD}_{rel} > 0$)**
- **Is in dB**
- **good for PASS/FAIL decisions**





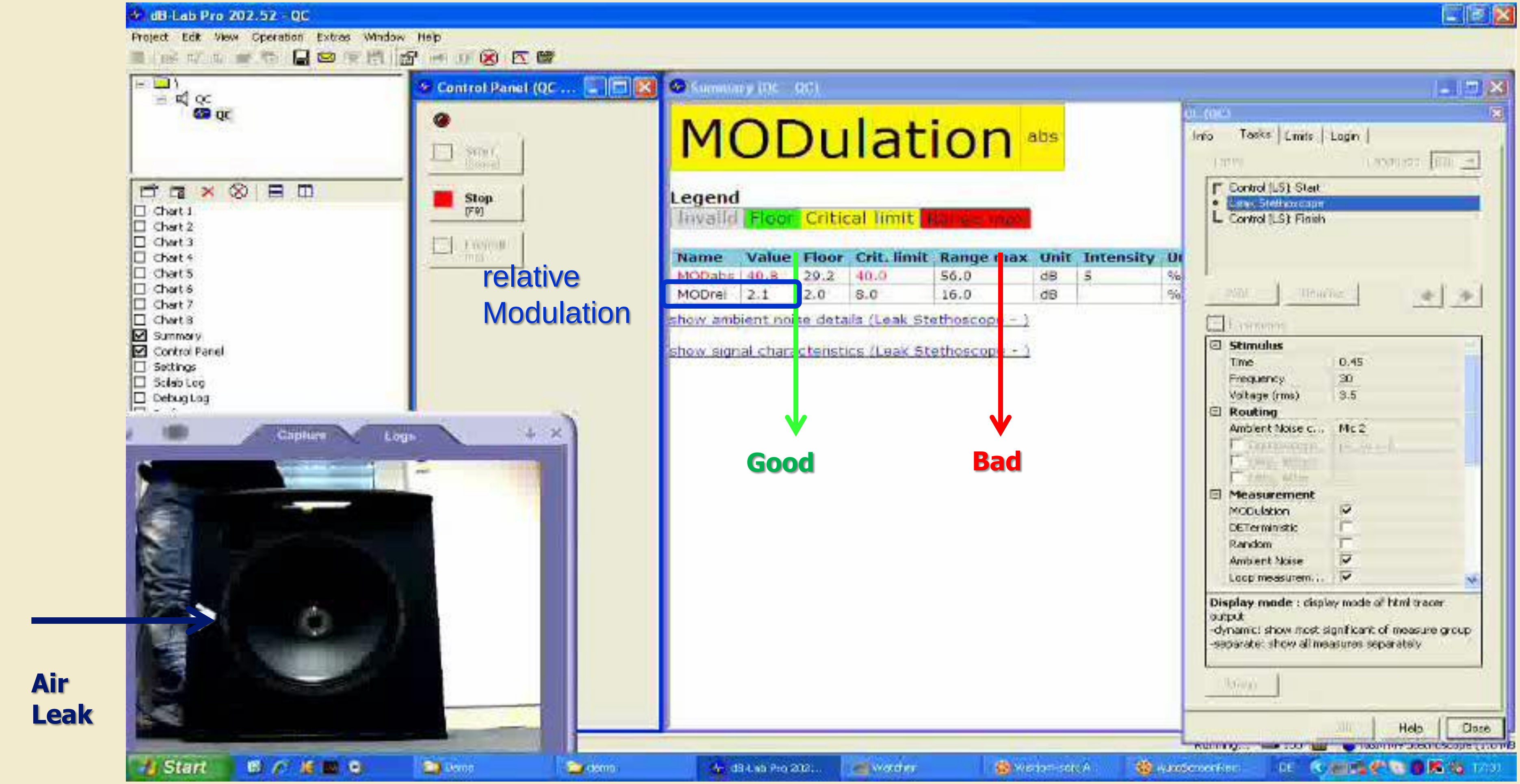
Combining Subjective and Objective Assessment



Objectives:

- Auralization of Irregular Distortion
- Ear Protection
- Signal Transformation
- Defect Localization
- Diagnostics

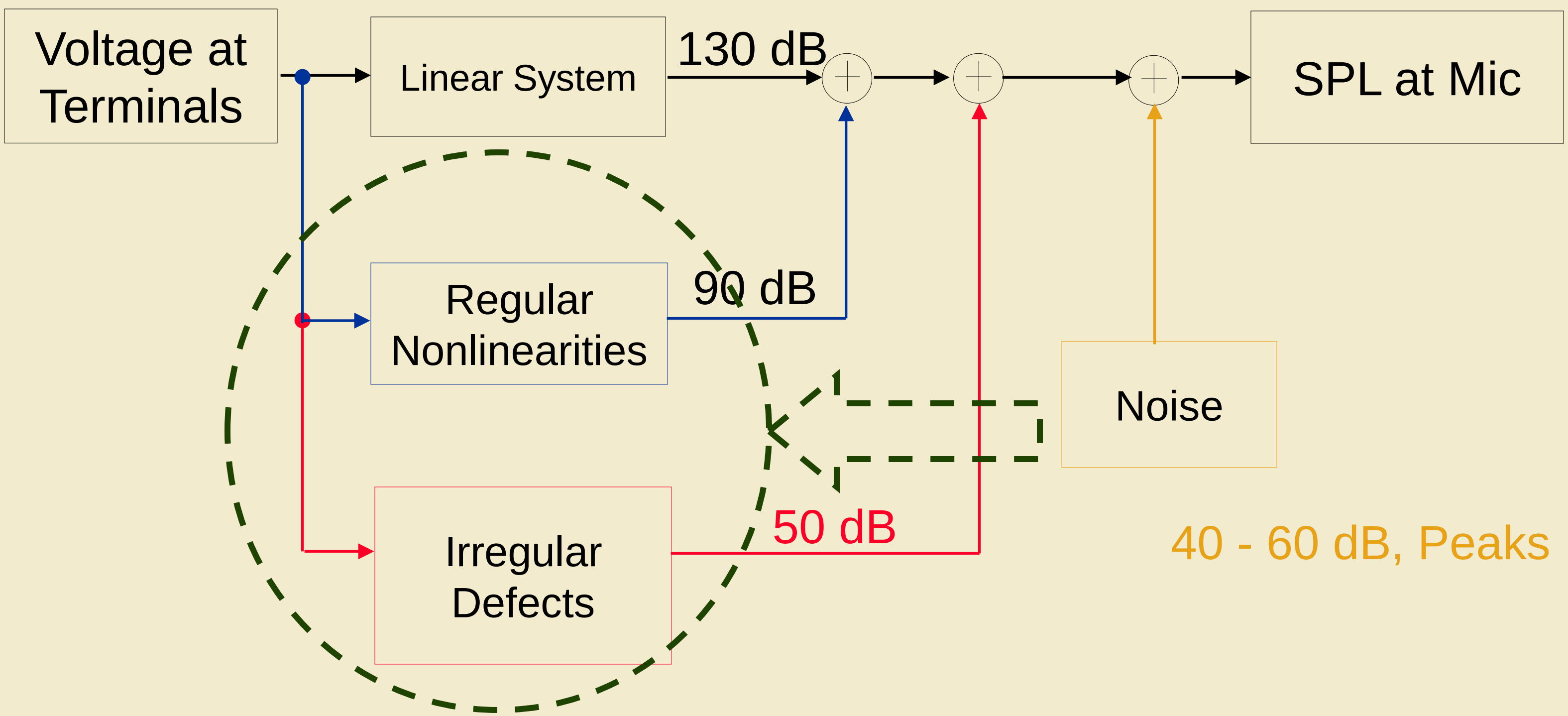
Localization of Loudspeaker Defects



A sensitive Measurement system is not sufficient !

Coping with Ambient Noise

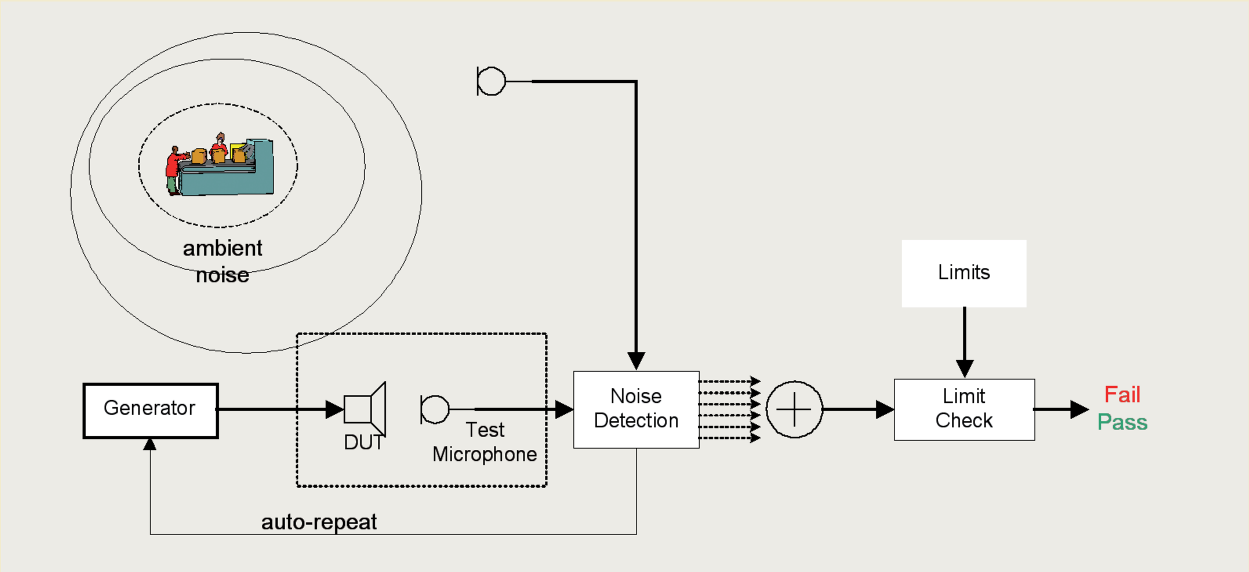
Sound Pressure Level of Signal Components



Problems:

- Symptoms of defects are very small (but still audible)
- Ambient noise in a production environment has similar properties

Solution: Ambient Noise Microphone



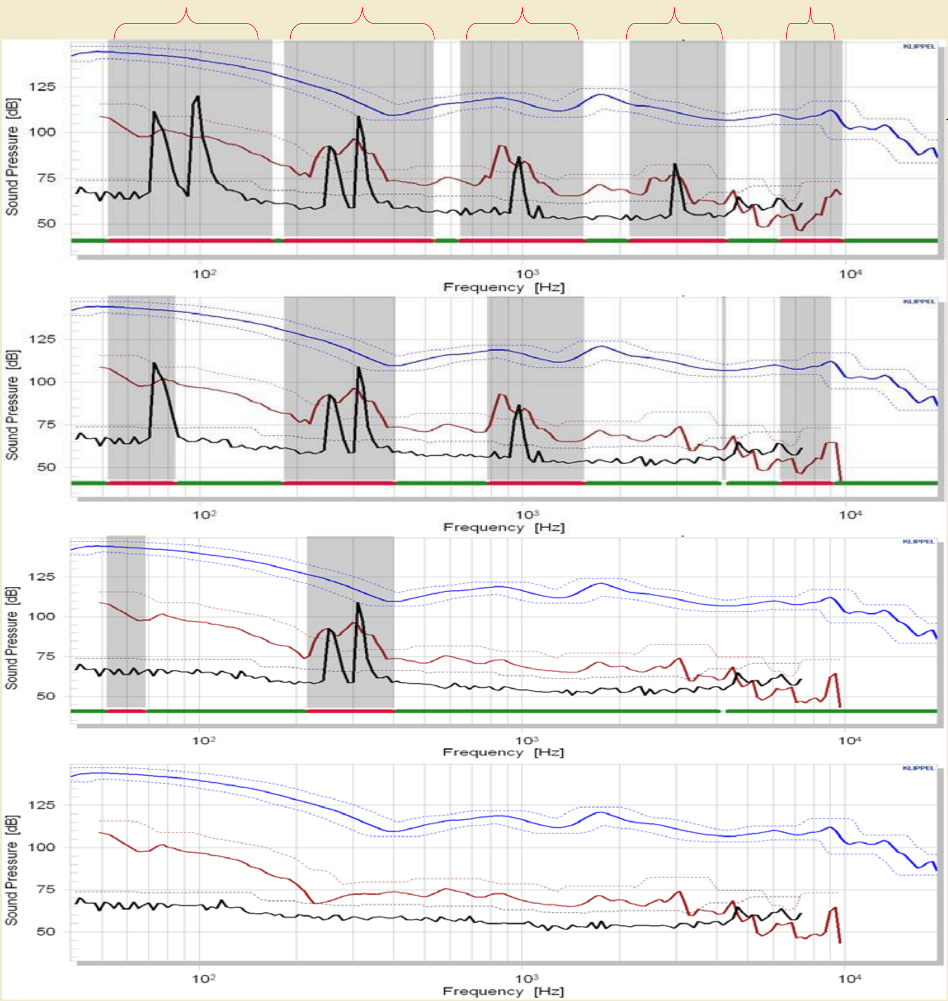
- Measure loudspeaker in the near field
- Measure noise / vibration in the far field
- Predict noise at test microphone
- Calculate impact on measured characteristics
- Store valid part of the measurement
- Repeat measurement automatically

→ Full noise immunity for random ambient noise

Merging Technique

repeating measurement automatically and accumulating valid parts

Ambient noise generated by permanent hand clapping

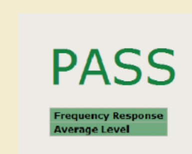


28 % valid

62% accumulated

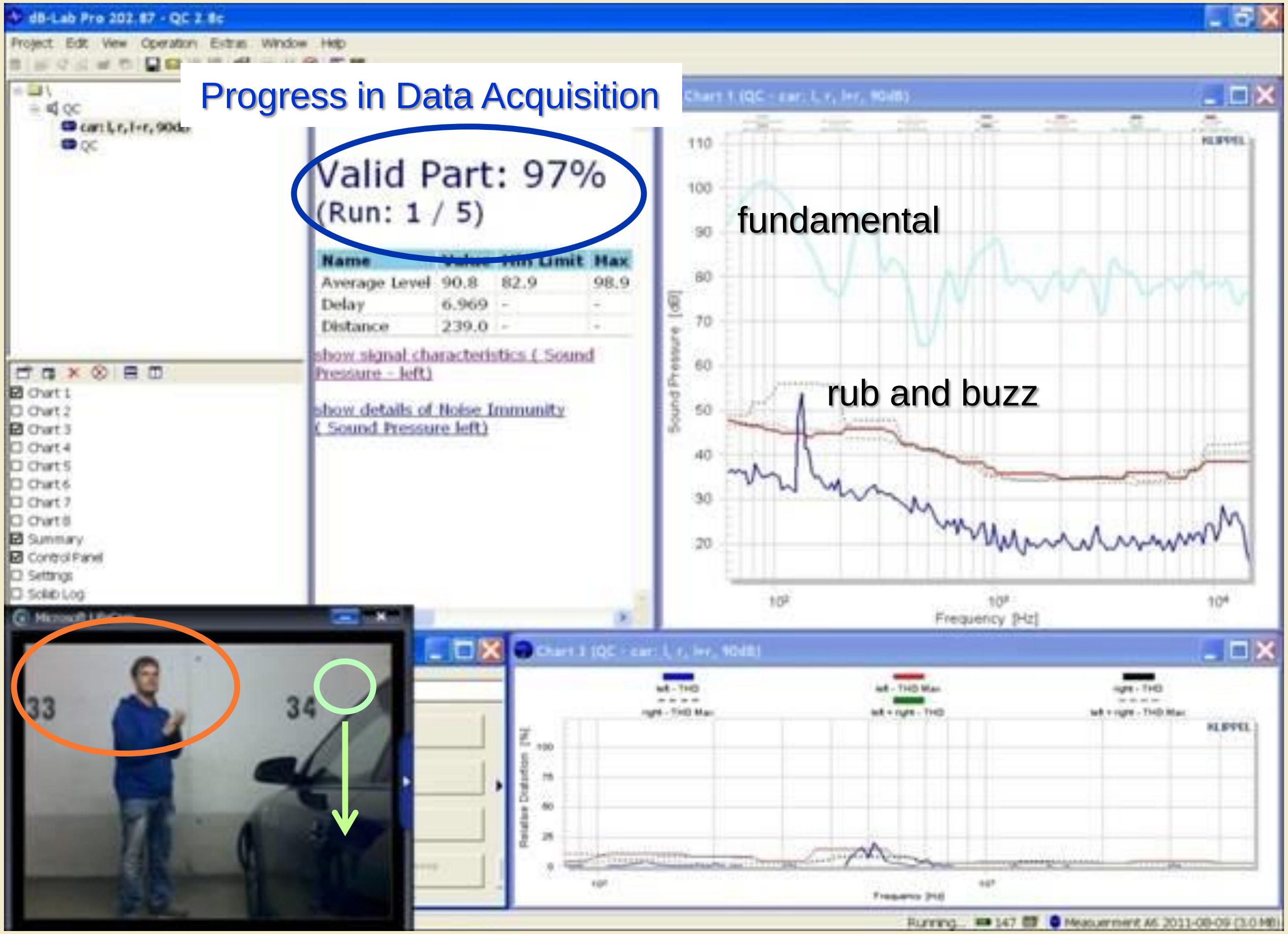
85% accumulated

100% valid



Full immunity against random noise

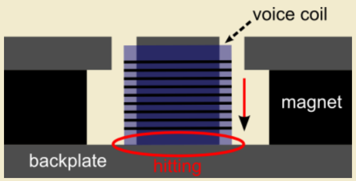
Sound Quality in the Car Interior



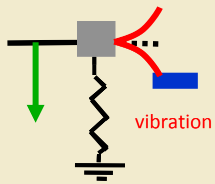
Simulation of Door Buzzing

How to fix the problem?

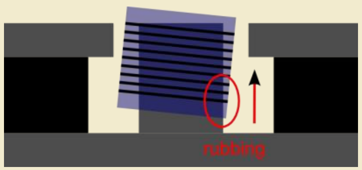
Root Cause Analysis of Loudspeaker Defects



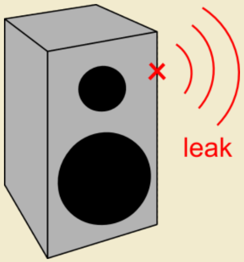
Bottoming



Buzzing



Coil Rubbing



Air Leak

Loose particle

Asymmetrical Suspension

Glue dispenser Problem

mass distribution on the cone

Missing screw

dirty storage condition

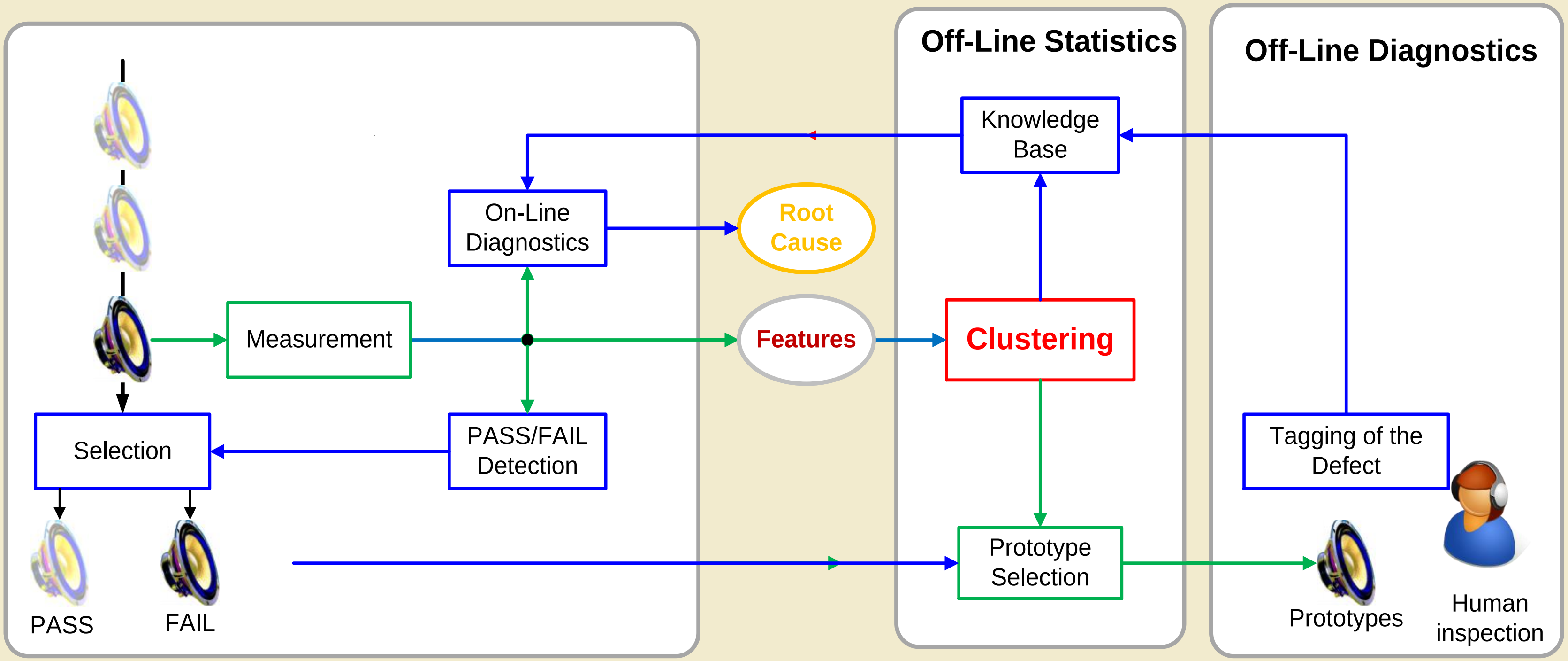
Design

Supplier

Qualtiy Inspection of Incoming Parrts

Manufacturing (Process Control)

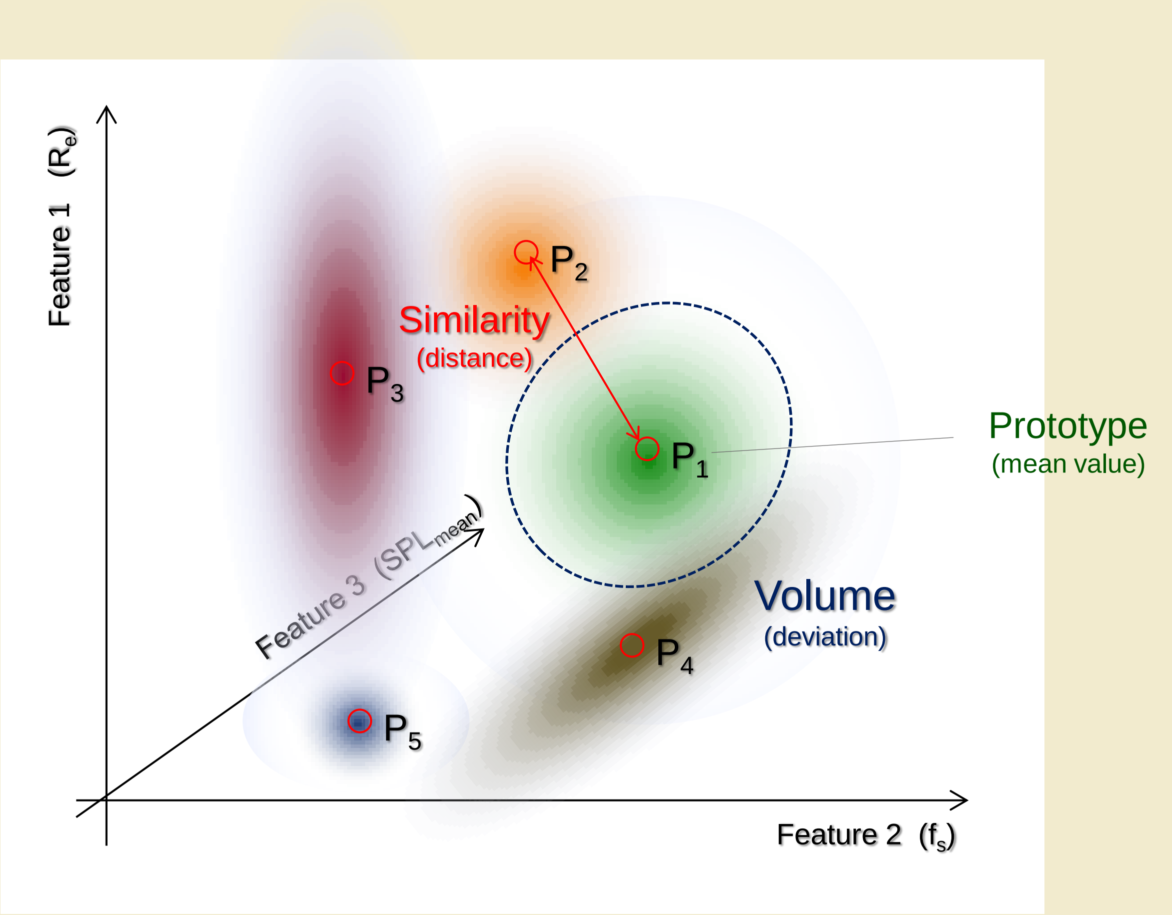
Automatic Learning from Manufacturing



1st step: Automatic clustering of the raw data
2nd step: Prototype selection (best representative of the cluster)
3rd step: Human inspection and tagging of the defect
4th step: Updating the knowledge base for on-line diagnostics

Clustering of the DUTs
in the Feature Space

Clustering is a statistical process of separating devices under test (DUTs) into subgroups wherein all members of one cluster have similar properties but are very different to the members of other clusters.



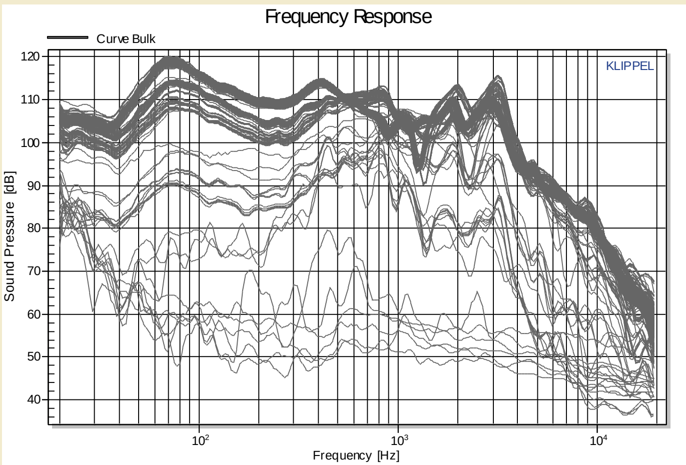
Results of the formal cluster analysis:

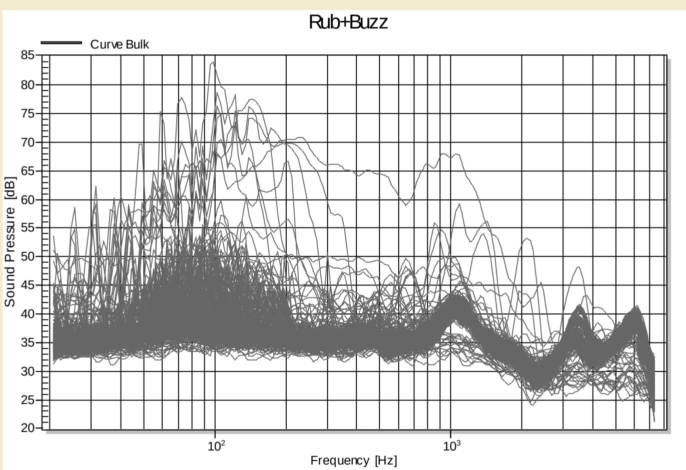
- Total number of defect classes
- Devices representing each class
- Properties of the good units
- Significant features
- Related or similar defects

tagging

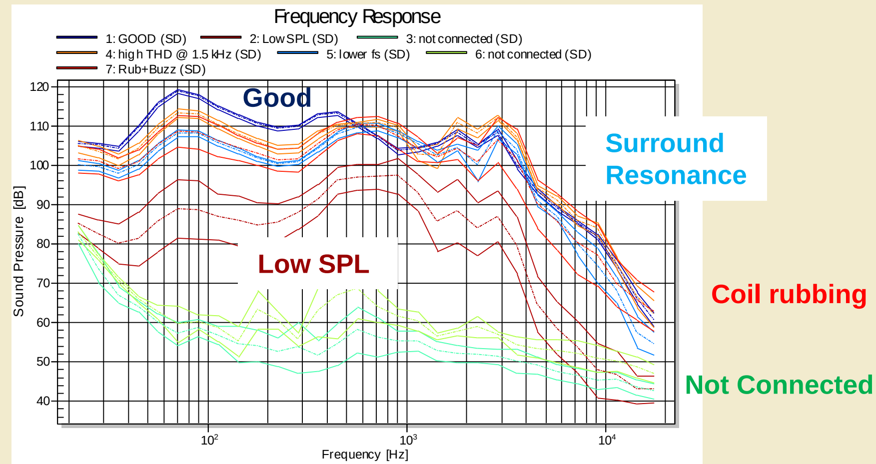
Clustering

Raw Measurement Data (300 DUTs)

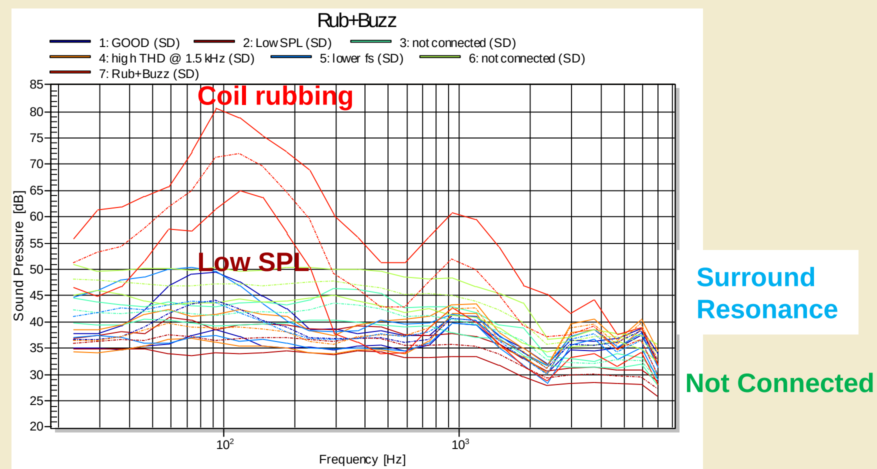




Results of the Clustering

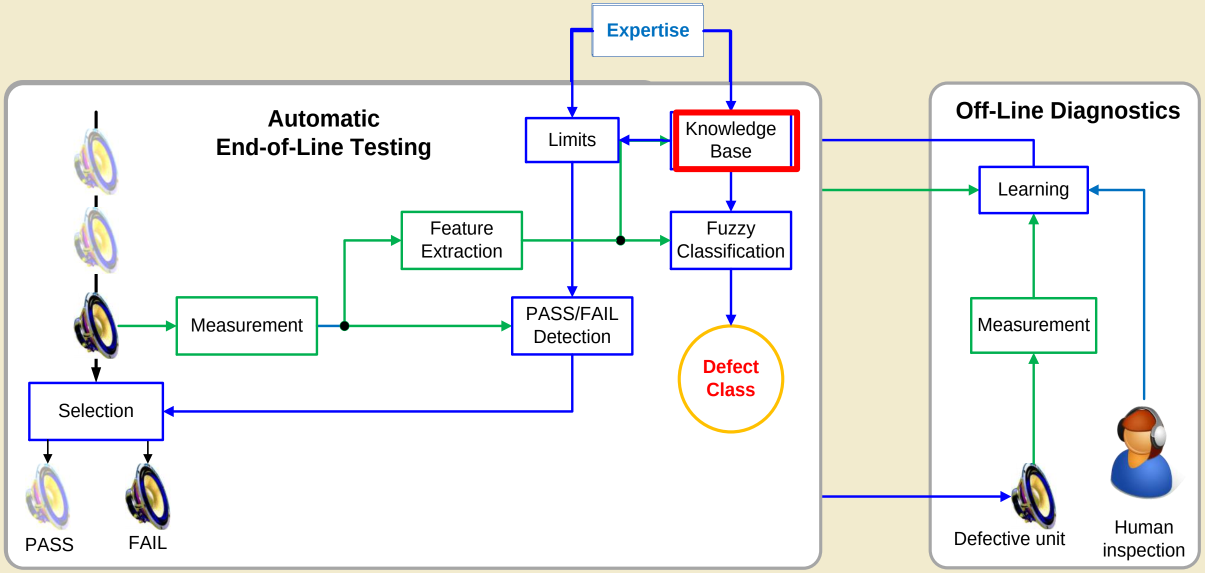


Good



Automatic Classification of Defects

1st source: theoretical knowledge in engineering (static)



2nd source: practical experience in manufacturing (dynamic)

Irregular Loudspeaker Distortion

Summary

- are related with loudspeaker defects
- not found in approved prototypes, golden reference unit
- are caused by manufacturing, overload, ambient conditions
- are not directly related to cost, size, weight
- are difficult to model and not predictable
- depend on the operation condition (e.g. orientation + loose particles)
- are time variant (aging) and usually become worse over time
- generate impulsive distortion with high crest factor but low energy
- are inacceptable if detected by customer

Conclusions

- Defective loudspeakers with irregular distortion should not be shipped to the customer even if the symptoms are inaudible
- Sensitive Measurement techniques are required more sensitive than the ear of the customer
- Time domain analysis is required to consider transient properties of the symptoms
- Reliable measurements require automatic detection of invalid tests corrupted by ambient noise in a production environment
- Production limits depend on the target application
- The human operator works on the diagnostic station and provides information for the knowledge base
- Automatic defect classification shows the root cause of the defect
- Process control ensures high yield rate in production

Many thanks !